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Parts I and II

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DESIGN GUIDE FOR THE USE OF STRUCTURAL SHAPES IN AIRCRAFT APPLICATIONS

Part I – Selection Criteria for Structural Shapes and Tubing

Part II – Manufacturing Methods for Structural Shapes and Tubing

by
T. G. Byrer, et al.

BATTELLE
Columbus Laboratories
505 King Avenue
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TECHNICAL REPORT AFML-TR-73-211

September, 1973

AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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October 11, 1973

Air Force Materials Laboratory
Manufacturing Technology Division
Wright-Patterson Air Force Base,
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Attention Mr. T. S. Felker, AFML/LTM

Gentlemen:

Design Guide on Contract F33615-71-C-1929

In accordance with the terms of the above contract, 225 copies of the "Design Guide for the Use of Structural Shapes in Aircraft Applications" have been printed in final form and approximately 125 copies have been distributed according to the distribution list which accompanies this letter. The additional 100 copies will be retained at Battelle's Columbus Laboratories for future distribution subject to your request.

This Design Guide, which has been prepared in cooperation with both aircraft manufacturers and suppliers of extruded and form rolled shapes, is the first document of its kind to provide the aircraft designer and structural shape manufacturer with a comprehensive review of the information gathered over the last 15 years as a result of Manufacturing Methods programs conducted under U. S. Air Force sponsorship. As a result of industrial participation in preparing this Design Guide, we are hopeful it will find widespread use in the aircraft industry and assist design engineers in learning more readily of the capabilities for structural shape manufacture in the U.S.

It has been our pleasure working with you in preparation of this document. Future requests for copies of this document should be directed to the Metalworking Section, Battelle's Columbus Laboratories.

Sincerely yours,

Tom Byrer

T. G. Byrer
Associate Manager
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TGB/bjs

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DESIGN GUIDE FOR USE OF STRUCTURAL SHAPES IN AIRCRAFT APPLICATIONS

by

T. G. Byrer, et al.

FOREWORD

This Final Technical Report covers the work performed under Contract F33615-71-C-1929 from August 1, 1971, through July 30, 1973.

This contract with Battelle's Columbus Laboratories was initiated under Manufacturing Methods Project 245-1, "Establish Properties of, and Manufacturing Methods for, Complex Structural Shapes". It was administered under the technical direction of Mr. T. S. Felker of the Metals Branch (LT) Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program was carried out by Battelle's Metalworking Section, Mr. R. J. Fiorentino, Manager. Mr. T. G. Byrer, Associate Manager, Metalworking Section, directed the program and was Principal Investigator. Authors of the Sections are:

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Martin-Marietta Aluminum Incorporated, Torrance, California

Rockwell International Corporation, Los Angeles Division, Los Angeles, California.

In addition, Mr. Kenneth G. Hookanson of Fort Lauderdale, Florida, and former General Manager, ITT Harper Company, Morton Grove, Illinois, as a technical consultant, reviewed Part II, Section 1.

The authors also wish to acknowledge the contribution of Ms. Rebecca Scott, Secretary, Metalworking Section, who provided invaluable assistance in preparing this manuscript, and Mr. Paul Grandinetti, Technical Illustrator, who designed the cover of this report.

This Technical Report has been reviewed and approved.

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ABSTRACT

A two-part Design Guide has been compiled to provide technical information and data in the production of structural shapes and tubing for aircraft and aerospace requirements. Part I provides selection criteria for shapes and tubing based on availabilities, design tolerances, and mechanical and physical properties. Part II discusses manufacturing methods for fabricating structural shapes and tubing, namely, extrusion, drawing, and form rolling. Also Part II reviews competitive processes for manufacturing structural type components. This Design Guide is intended to assist design engineers in assessing the availability and properties of materials being considered in new or modified aircraft and aerospace systems, and to assist potential manufacturers and suppliers in assessing equipment, tooling, and processing requirements for fabricating structural shapes and tubing. Materials for aerospace requirements covered in this document include high-strength aluminum alloys, titanium alloys, steels, superalloys, refractory metals, and beryllium.

PROGRAM SUMMARY

This Manufacturing Methods program was undertaken to compile a manufacturing process manual (now designated as a Design Guide) of technical information and data on the production of structural shapes and tubing for aircraft and aerospace requirements. As evidenced by the division of this Design Guide into two parts, it is intended first to provide design engineers with information on the availability of selected materials in shape or tubular form, and properties of these materials for consideration in new or modified aircraft and aerospace designs (Part I) and second to enable potential manufacturers and suppliers to assess equipment, tooling, and process requirements necessary to fabricate structural shapes and tubing to meet these aircraft system requirements (Part II).

In preparing this document, all available open literature including government reports in the areas of interest during the period of 1950 to 1973, was reviewed and conferences were held with design personnel in several aircraft companies. After completion of the Design Guide in its initial form, subcontracts were entered into with several companies and a private consultant to review the document and its contents, and to indicate methods of improving the layout to make it of most use to both the aircraft designer and the manufacturer.

Part I is aimed at assistance in selecting materials for use as structural shapes and tubing. Materials covered include high-strength aluminum alloys, titanium alloys, steels, superalloys, refractory metals, and beryllium. Section 1 describes the availability of these materials in simple structural shape or tubular form in terms of size, section thickness, and status of commercial availability. Also included is a list of manufacturers who can supply extruded shapes and tubing both in the U. S. and abroad. Section 2 is composed of composite specifications concerning shape design limitations, dimensional tolerances, obtainable surface quality, etc. In Section 3, design properties have been compiled and tabulated to help the design engineer to quickly review mechanical- and physical-property data of importance in aircraft design. Section 4 contains in capsule form a comparison of competitive or alternative processes to the manufacture of structural shapes by extrusion or form rolling. The present production status of these forming methods is reported, and current production capabilities are summarized.

Part II is concerned with manufacturing methods for the fabrication of structural shapes and tubular products. Sections 1, 2, and 3 describe the processing techniques utilized in manufacturing structural shapes by extrusion, form rolling, and drawing, respectively. Process descriptions and data sheets are intended to provide present and potential suppliers of these fabricated parts with the basic process conditions necessary for manufacturing aircraft shapes and tubing. Section 4 is a more detailed elaboration on the comparable section in Part I concerning alternative or competitive processes. These more detailed discussions provide the reader with a better understanding of alternative processes and the various limitations and capabilities of each.

Future Advanced Manufacturing Methods

In the course of preparing this Design Guide, the authors had many opportunities to discuss the present status of technology in the areas of extrusion, form rolling, and drawing with both manufacturers and users of structural shapes and tubing. On the basis of current markets for structural shapes in both military and commercial aircraft manufacture, which are quite limited at the present time, one could conclude that (1) present manufacturing methods for these kinds of products are generally adequate for present demands, and (2) the user over the years has acquired the necessary machine tools and other equipment that are necessary to process the as-fabricated structural shape into the product needed for assembling into an aircraft structure. The limited number of manufacturing-method-improvement studies currently underway in these areas reflect the present market situation for shapes and tubing in aircraft systems.

On the horizon, however, are several processing techniques (which are discussed in Part II of this Design Guide) that suggest some radical changes in the methods being used and that potentially could significantly reduce the cost of these products for aircraft manufacture. In view of present markets, extensive studies in these areas are difficult to justify. However, the premise of many manufacturing technology programs undertaken by the Air Force (and other U. S. Government agencies) is to maintain military preparedness at a high level in the event of a national emergency. This situation, of course, remains unchanged. Thus, it is important that as new processes and process improvements come to the forefront, they be assessed in terms of manufacturing feasibility and

cost effectiveness to define their applicability to (1) future aircraft and aerospace systems and (2) existing aircraft systems in the event their manufacture must be suddenly accelerated.

Several areas bear mentioning at this point. For example, limited studies in the lubricated extrusion of hard-aluminum alloys show considerable promise for greatly increasing the throughputs of extruded aluminum shapes over those currently available by the conventional techniques. Computer-aided techniques for designing extrusion dies for lubricated extrusion may provide further cost savings. In the event substantial markets open up again for these types of products, significant cost savings could be realized if these techniques were developed for ready utilization in industry when the need arises.

The second area is that of continuing efforts to improve quality of extruded high-temperature, high-strength materials. At the present time and for some time past, extruded shapes in these materials must be completely machined on all surfaces in order to meet aircraft requirements. While utilization of shape drawing to improve the quality of these products has been demonstrated, the cost of these operations in light of current markets has prevented their implementation in industry to date.

The ability to use extrusion to provide an infinite variety of structural configurations at rather low tooling costs in comparison with those of many other potentially comparable processes gives it a decided edge as a method for manufacturing structural shapes for aircraft. Thus, it is still desirable to pursue developmental efforts to upgrade the extrusion process aimed at improving dimensional tolerances and surface finishes obtainable on extruded products. Recent Air Force-sponsored efforts in isothermal extrusion, development of new die materials, and other tooling components are evidence of steps in this direction.

A new area, as yet unexplored, is that of warm extrusion of structural shapes. As Part II indicates, problems of tool life in hot extrusion as well as material-contamination problems due to the high temperatures involved have prevented the manufacture of small-tolerance, high-precision shapes in the as-extruded form. Attempts to develop high-temperature lubricants and new die materials that are utilized at these high temperatures have met with only marginal success. Thus, it is reasonable to conclude that efforts should be devoted to use lower extrusion temperatures, for example 1200 to 1600 F with titanium alloys, as a means of reducing the contamination problem and prolonging die life through lower temperature differential between the heated billet and tooling. For example, current efforts in an Air Force-sponsored investigation of the warm hydrostatic extrusion of titanium alloy tubing have shown considerable promise. This work, as the technology develops, could show the way toward improved tool life and better as-extruded quality in structural-shape manufacture through warm-extrusion techniques.

One further area concerns the continuation of process improvement studies and the availability of modern extrusion equipment. Many of the extrusion presses in the United States, particularly in the larger sizes of 3000 tons or above, are nearly 25 years old. With present markets, there is evidence of limited utilization of some of this equipment. If this situation continues, it is reasonable to expect that maintenance and repair (which will become more frequent as the equipment ages) needed to maintain this equipment in top-notch condition, will likely not be done or constitute only minimal effort. Thus, it is conceivable that with present trends some of this equipment could be nonoperating or require considerable repair work at some time in the future when military needs are suddenly imminent.

However, if technology-improvement efforts aimed at greater throughput at lower costs can continue, the danger of possible reduced availability of efficient, operable equipment in the event of a national emergency is lessened. This would be true, of course, only if new process advances are assimilated into the existing industrial base as they are perfected.

In summary then, it is urged that continued efforts be made to maintain a high-quality production capability in the United States for manufacturing structural shapes, and that efforts also be continued to upgrade and improve these processes on the basis of potential long-range requirements. Continuation of these efforts will insure that a viable production base for the manufacture of structural shapes and tubular products will be available and prevent the need for reliance on sources outside the United States in the event that large markets do develop some time in the future. Data contained in this Guide constitute ample evidence of the importance of the extensive manufacturing process programs over the past 20 years largely under Air Force sponsorship. The technological expertise that has been developed must be maintained, and can be assured only through continuing efforts to upgrade the processing techniques being used as well as the equipment requirements needed for these processes.

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PART I

SELECTION CRITERIA FOR STRUCTURAL SHAPES AND TUBING

Section 1 – Availability of Extruded, Drawn, and Form Rolled Structural Shapes

Section 2 – Tolerances and Design Criteria

Section 3 – Design Property Data for Structural Shapes and Tubing

Section 4 – Summary of Competitive Processes

SECTION 1

AVAILABILITY OF EXTRUDED, DRAWN, AND FORM-ROLLED STRUCTURAL SHAPES

by

Gerald A. Gegel

SECTION 1

AVAILABILITY OF EXTRUDED, DRAWN, AND FORM-ROLLED STRUCTURAL SHAPES

INTRODUCTION

Extruded, drawn, or form-rolled structural shapes can be supplied in a wide variety of configurations from most aerospace alloys. Most of these configurations are either basic angle, tee, or channel shapes or combinations of these shapes. A number of the steel, titanium, and nickel-base alloys are available as standard in-stock shapes from some producers. Refractory-alloy extruded shapes, with the exception of beryllium and its alloys, are available only on a special-order, best-efforts basis.

Depending on alloy composition, available as-extruded section thicknesses generally vary from 1/8 to 3 inches within circumscribing circles of 1-1/2 to 20-1/2 inches in diameter. A significant portion of the extruded structural shapes used fit within a 3 to 9-inch-diameter circle. The extruded parts can generally be reduced in section thicknesses 50 percent by drawing. The minimum section thickness available for form-rolled products is about 0.060 inches.

The maximum lengths currently supplied vary from 20 to 75 feet for as-extruded shapes. Of course, the maximum length of extrusion that can be made is a function of both the cross-sectional area of the shape and the size of the billet that can be accommodated by the extrusion equipment. If the extrusions are to be annealed and straightened, the maximum length now obtainable is about 60 feet. If the extruded and/or drawn shapes are to be supplied to the customer in a heat-treated condition, the lengths available will be shorter. Here, the length limitations are dictated by the size of heat-treating facilities.

Theoretically, the length produced with form-rolling techniques is unlimited. However, from a practical standpoint, a limit of about 25 feet exists because of available heat-treatment and materials-handling equipment.

EXTRUSION FACILITIES

A list of major U.S. and foreign extrusion-press facilities and their capabilities are presented in Tables 1 and 2. The listings primarily reflect those facilities that extrude titanium, steel, and other high-strength aerospace alloys or those that have equipment capable of making very large aluminum alloy extrusions. Although the facilities of Cameron Iron Works, Incorporated are primarily used for the extrusion of steel pipe, the equipment has been used to extrude large titanium structural shapes.

AVAILABILITY OF STRUCTURAL SHAPES

The information compiled in the various Tables of Section 1 will allow the design engineer to ascertain the size availability of extruded or form-rolled shapes. All of the data presented are based on the geometric limitations of the forming processes. Reference to Figure 1 will illustrate the meaning of the data terms used in the compilations.

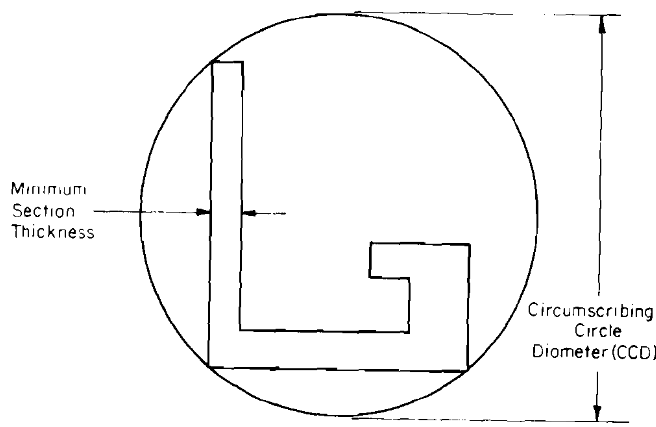


FIGURE 1. NOMENCLATURE USED IN DEFINING SHAPE SIZE LIMITATIONS

The circumscribing circle diameter (CCD) is the minimum diameter of a circle which will completely enclose the part cross section. For a given range of CCD's, there is a minimum cross-sectional area which can be extruded, drawn, or form-rolled because of force limitations on available equipment. In addition, there is a minimum section thickness that may be practically obtained because of pressure limitations and quality of the finished part. The maximum cross-sectional area obtainable for a specific product geometry is a function of the length of the product desired and the billet-size capability of the equipment of which the extrusion is being made.

TABLE 1. MAJOR EXTRUSION PRESS FACILITIES FOR EXTRUDING STRUCTURAL SHAPES AND TUBING (U.S.A. ONLY)

Company and Location	Extrusion Press Capacity, tons	Liner Diameters, inches	Maximum Billet Length, inches	Maximum Circumscribing Circle[a], inches	Principal Materials Extruded
Allegheny-Ludlum Steel Corp. Watervliet, New York	2,200	5-5/8 to 8-1/2	15 to 26	3-1/2 to 5	Steel, Ti alloys, Ni-base alloys
Aluminum Company of America Lafayette, Indiana	14,000[b] 15,500	15 to 33 15 to 33	79-3/4 79-3/4	14 to 32 14 to 32	Aluminum Aluminum
Armco Steel Corporation Baltimore, Maryland	3,000	6 to 10-5/16	24	5-1/2 to 9	Steel, Ti alloys, Ni-base alloys
Babcock and Wilcox Company Beaver Falls, Pennsylvania	2,500	4 to 8-1/2	10 to 28	2-1/4 to 6-1/2	Steel, Ti alloys
Kawecki Berylco Reading, Pennsylvania	1,700	3-3/8 to 7	16	5-1/2	Beryllium and beryllium alloys
Brush-Wellman Elmore, Ohio	3,000	8-1/2 to 10-1/2	n.a.	n.a.	Beryllium and beryllium alloys
CONALCO Madison, Illinois	14,000[b] 5,500[b] 3,000[b]	16 to 32 12 to 18 8 to 12	74-13/16 40 36	15 to 31 n.a. n.a.	Aluminum Aluminum Aluminum
Cameron Iron Works, Inc. Houston, Texas	35,000[c] 20,000[c]	n.a. n.a.	n.a. n.a.	7-3/4 to 36	Steel pipe
Canton Drop Forge Canton, Ohio	5,500 3,000	7-1/2 to 19 n.a.	44 n.a.	12 n.a.	Steel, other high-strength materials
Curtiss-Wright Corporation Buffalo, New York	12,000[b]	8 to 28	68	5-1/2 to 21-1/2	Steel, Ti alloys, Ni-base alloys
Taber Metals, Incorporated[c] Russellville, Arkansas	8,000	13 to 20 10 x 28	n.a. n.a.	20 26 width	Aluminum and magnesium
International Nickel Company Huntington, West Virginia	4,000	7 to 12	30	6 to 10-1/2	Nickel-base alloys
ITT Harper Morton Grove, Illinois	2,100	5 to 8-1/8	16 to 27	1-1/2 to 6-1/2	Steel, Ti alloys, Ni-base alloys
Kaiser Aluminum Halethorpe, Maryland	8,700	14 to 20	60 to 65	19	Aluminum
Martin-Marietta Aluminum Torrance, California	14,000[b] 8,100[b] 3,850	14 to 32 12 to 19 6 to 13	75 65 36	12 to 30 10 to 17 11	Aluminum Aluminum Steel, Ti alloys
Reactive Metals Niles, Ohio	3,850 2,500	2 to 13-1/2 4 to 8	31 26	9 6-1/2	Titanium Titanium
TMCA Toronto, Ohio	2,200	4 to 8	26	5-1/4	Titanium
Viking Metallurgical Corp. Verdi, Nevada	3,300	n.a.	n.a.	n.a.	Superalloys

(a) Circumscribed circle diameters are dependent upon tooling setups in individual extrusion presses and are "roughly", in relation to billet sizes, about 88 percent of the billet diameter.
(b) U.S. Air Force-owned.
(c) Plant leased from Dow Chemical, U.S.A.
(d) Vertical hydraulic presses that are used for both forging and back extrusion of seamless pipe and some shapes.

TABLE 2. MAJOR EXTRUSION PRESS FACILITIES (OUTSIDE U.S.A.)

Company and Location	Extrusion Press Capacity, tons	Liner Diameters, inches	Maximum Billet Length, inches	Maximum Circumscribing Circle[a], inches	Principal Materials Extruded
Alusuisse Schweizerische Aluminum AG, Chippis, Switzerland	7,200	20	56	n.a.	Aluminum
CEFILAC Persan, France	1,650	5 to 8-1/2	n.a.	n.a.	Steel and specialty alloy shapes and tubes
Chesterfield Tube Co, Ltd. Chesterfield, England	3,300	n.a.	n.a.	n.a.	Steel shapes and tubes
Dalmine S.P.A. Costa Volpino, Italy	3,300	10.4 to 14.4	44	n.a.	Steel tubes and shapes
Henry Wiggin & Co., Ltd. Glasgow, Scotland Hereford, England	2,420 5,500	n.a. n.a.	n.a. n.a.	n.a. n.a.	Nickel-base alloys
Hoesch-Schwerte AG, Schwerte, Germany	1,980	n.a.	n.a.	6	Steel shapes and shaped tubing
Kobe Steel, Ltd. Kobe, Japan	6,050	10.4 to 15.4	54	n.a.	Steel tubes and shapes
Light Metals Extrusion Development Co, Ltd. Japan	9,500	n.a.	n.a.	n.a.	Aluminum
Nippon Steel Corporation Hikari, Japan	2,475	10 maximum	31	n.a.	Steel tubing and shapes
Sandvik Steel Works Sandviken, Sweden	3,300 1,375	7.8 to 13.8 5 to 5.7	40 n.a.	n.a. n.a.	Steel tubes and shapes, principally stainless steels
Sanyo Special Steel Co, Ltd. Himeji, Japan	1,375 2,200	5.4 to 5.8 6 to 10	n.a. n.a.	2.8 5.9	Specialty steel tubing
Schoeller Bleckmann Stahlwerke AG, Austria	3,300	n.a.	n.a.	n.a.	Steel tubes and shapes
Sumitomo Metal Indus, Ltd. Amagasaki, Japan	2,475 3,410	n.a. n.a.	n.a. n.a.	6 9.2	Steel tubes and shapes
Tubacex, C.E. de Tubos Por Extrusion, S.A. Llodio, Spain	3,400	8.8 to 14	n.a.	n.a.	Carbon and alloy steel tubing
Vallourec Montbard, France	3,300	n.a.	n.a.	n.a.	Steel tubing

(a) Circumscribed circle diameters are dependent upon tooling setups in individual extrusion presses and are "roughly", in relation to billet sizes, about 88 percent of the billet diameter.

PROCEDURES FOR UTILIZING SECTION 1 TABULATIONS

The data presented here define size availability for the alloy categories listed in Table 3. The recommended procedure for using the data consists of the following steps:

(1) Determine
   (a) Diameter of circle (CCD) that will fully enclose the desired part shape
   (b) Cross-sectional area of shape
   (c) Minimum leg thickness of the part.

(2) Referring to Tables 3 through 10 for the appropriate alloy category, find the CCD into which the part will fit and determine if:
   (a) The cross-sectional area of the desired shape is equal to or greater than the minimum cross-sectional area listed and
   (b) The minimum section thickness of the part is equal to or greater than the minimum listed.

These tables indicate the present manufacturing capability for the forming processes considered, based on U. S. equipment capabilities only. The design engineer will be able to determine the manufacturing capability for the size desired ranging from that of standard production practices (Category A) to that available only on a best-efforts basis (Category D).

Limitations on shape configuration are *not* reflected in the availability data. The designer should refer to Section 2 of this Manual for these guidelines.

TABLE 3. ALLOY CATEGORIES

Category	Typical Alloys in This Category
Low alloy carbon steels	41XX, 43XX, 86XX
Precipitation hardening stainless steels	17-4PH, PH15-7Mo
Stainless steels	Types 200, 300, and 400
Titanium alloys	All except CP grades
Nickel- or cobalt-base alloys	Hastelloy X, Inconel-600, L-605
High-temperature refractory alloys	All Cb, Ta, and Mo alloys
Lightweight refractory alloys	Be alloys, Lockalloy
Aluminum alloys	6061, 2014, 2024, 7075

MANUFACTURING CAPABILITY CODE FOR TABLES 4 THROUGH 13

A – commercially available; standard extrusion practice.
B – manufacturing process available; special order item subject to negotiation; availability may depend on configuration of desired shape.
C – manufacturing process developed but not reduced to standard practice; production capability not fully demonstrated.
D – no present production capability; fabricated on a "best-efforts" or "research-and-development" basis only.
O – beyond capabilities of present production equipment.
NA – not available.

TABLE 4. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES, SEMIHOLLOW SHAPES, ROD AND BAR FOR 6005, 6061, 6070, AND 6351 ALUMINUM ALLOYS*

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability (1)		
			Extruded	Extruded and Drawn	Form Rolled
0.5 to 2		0.040	A		
2 to 3		0.045	A		
3 to 4		0.050	A		
4 to 6		0.062	A		
6 to 7		0.078	A		
7 to 8		0.094	A		
8 to 10		0.109	A		
10 to 11		0.125	A		
11 to 12		0.156	A		
12 to 24		0.188	A		

* Aluminum Standards and Data, published by Aluminum Association, 1971, Alcoa Product Data, Section AD2A, published by ALCOA, June 28, 1968.

TABLE 5. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES, SEMIHOLLOW SHAPES, ROD AND BAR FOR 2014, 5086, AND 5454 ALUMINUM ALLOYS*

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability (1)		
			Extruded	Extruded and Drawn	Form Rolled
0.5 to 2		0.040	A		
2 to 4		0.050	A		
4 to 5		0.062	A		
5 to 6		0.078	A		
6 to 7		0.094	A		
7 to 8		0.109	A		
8 to 11		0.125	A		
11 to 12		0.156	A		
12 to 20		0.188	A		
20 to 24		0.250	A		

* Aluminum Standards and Data, published by Aluminum Association, 1971, Alcoa Product Data Section AD2A, published by ALCOA, June 28, 1968.

TABLE 6. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES, SEMIHOLLOW SHAPES, ROD AND BAR FOR 2024, 2219, 5083, 5456, 7001, 7075, 7079, AND 7178 ALUMINUM ALLOYS*

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability (1)		
			Extruded	Extruded and Drawn	Form Rolled
0.5 to 2		0.040	A		
2 to 3		0.050	A		
3 to 4		0.062	A		
4 to 5		0.078	A		
5 to 7		0.094	A		
6 to 7		0.109	A		
7 to 8		0.125	A		
8 to 12		0.156	A		
12 to 17		0.188	A		
17 to 20		0.250	A		
20 to 24		0.500	A		

* Aluminum Standards and Data, published by Aluminum Association, 1971, Alcoa Product Data, Section AD2A, published by Alcoa, June 28, 1968.

TABLE 7. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FABRICATED FROM LOW ALLOY CARBON STEELS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability (1)		
			Extruded	Extruded and Drawn	Form Rolled
1" to 2" included	0.40	0.120	A	-	A
		0.062	C	A	A
	0.40	0.030	NA	NA	A
2" to 3" included	0.40	0.120	A	-	A
		0.062	C	A	A
		0.030	NA	NA	A
3" to 4" included	1.00	0.143	A	-	0
	0.50	0.125	NA	A	0
4" to 5" included	2.00	0.180	A	-	0
	0.5	0.125	NA	A	0
5" to 6" included		0.190	A	-	0
	0.5	0.125	NA	A	0
6" to 8" included	4.0	0.312	A	0	0
		0.250	B	0	0
8" to 10.75" included	5.0	0.312	A	0	0
		0.250	B	0	0
10.75" to 12.5" included	14.0	0.375	A	0	0
		0.300	B	0	0
12.5" to 16.5" included	31.0	0.375	A	0	0
		0.300	B	0	0
16.5" to 20.5" included	50.0	0.375	A	0	0
		0.300	B	0	0

TABLE 8. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM PRECIPITATION HARDENING STAINLESS STEEL

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability(1) Extruded	Extruded and Drawn	Form Rolled
1" to 2" included	0.75	0.188	A	-	A
	0.28	0.062	D		A
		0.040	NA	D	A
		0.030	NA	NA	A
2" to 3" included	1.5	0.250	A	-	-
		0.125	NA	A	A
		0.030	NA	NA	A
3" to 4" included	3.0	0.250	A	-	0
		0.125	NA	A	0
4" to 5" included	3.75	0.250	A	-	0
		0.125	NA	A	0
5" to 6" included	4.50	0.250	A	-	0
		0.125	NA	A	0
6" to 8" included	5.0	0.312	A	0	0
8" to 10.75" included	6.0	0.350	A	0	0
10.75" to 12.5" included	18.0	0.400	A	0	0
12.5" to 16.5" included	40.0	0.438	A	0	0
16.5" to 20.5" included	60.0	0.500	A	0	0

TABLE 9. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM STAINLESS STEELS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability(1) Extruded	Extruded and Drawn	Form Rolled
Up to 1" included	0.45	0.188	A	-	-
		0.125	NA	A	-
1" to 2" included	0.75	0.188	A	-	-
	0.5	0.125	NA	A	-
		0.030	NA	NA	A
2" to 3" included	1.13	0.188	A	-	-
	0.5	0.125	NA	A	-
		0.030	NA	NA	A
3" to 4" included	1.5	0.188	A	-	0
	0.5	0.125	NA	A	0
4" to 5" included	1.88	0.188	A	-	0
	0.5	0.125	NA	A	0
5" to 6" included	2.5	0.214	A	-	0
	0.5	0.125	NA	A	0
6" to 8" included	5.0	0.312	A	0	0
8" to 10.75" included	6.0	0.350	A	0	0
10.75" to 12.5" included	18.0	0.400	A	0	0
12.5" to 16.5" included	40.0	0.438	A	0	0
16.5" to 20.5" included	60.0	0.500	A	0	0

TABLE 10. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM TITANIUM ALLOYS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section* Thickness, inch	Manufacturing Capability(1)		
			Extruded	Extruded and Drawn	Form Rolled
1" to 2" included	0.280	0.125	A	-	-
	0.180	0.090	C	A	-
		0.060	D	C	A
		0.040	NA	D	B
2" to 3" included		0.125	A	-	-
		0.060	NA	C	A
3" to 4" included		0.143	A	-	0
4" to 5" included		0.180	A	0	0
5" to 6" included		0.214	A	0	0
6" to 8" included	5.0	0.312	A	0	0
		0.250	B	0	0
8" to 10.75" included	6.0	0.375	A	0	0
		0.300	B	0	0
10.75" to 12.5" included	28.0	0.438	A	0	0
		0.375	B	0	0
12.5" to 16.5" included	106.0	0.562	A	0	0
		0.438	B	0	0
16.5" to 20.5" included	154.0	0.750	A	0	0
		0.650	B	0	0

* Note: These dimensions do not reflect the amount of material (as much as 0.050 inch per surface) that must be removed from titanium extrusions to eliminate the alpha case and surface imperfections. This data represents as-extruded section thicknesses.

TABLE 11. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM NICKEL OR COBALT BASE SUPERALLOYS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability(1)		
			Extruded	Extruded and Drawn	Form Rolled
Up to 1" included					
1" to 2" included	2.00	0.400	A	NA	-
		0.040	NA	NA	A
2" to 3" included		0.500	A	NA	-
		0.040	NA	NA	A
3" to 4" included		0.500	A	NA	0
		0.450	D	NA	0
4" to 5" included		0.714	B	NA	0
5" to 6" included		0.857	B	NA	0
6" to 8" included	7.00	0.375	B	NA	0
8" to 10.75" included	8.5	0.438	B	NA	0
10.75" to 12.5" included	39.0	0.562	B	NA	0
12.5" to 16.5" included	190.0	0.750	B	NA	0
16.5" to 20.5" included	257.0	0.875	B	NA	0

TABLE 12. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM COLUMBIUM, MOLYBDENUM, AND TANTALUM ALLOYS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability[1]		
			Extruded	Extruded and Drawn	Form Rolled
Up to 1" included	0.3	0.187	D	NA	NA
1" to 2" included	0.6	0.250	D	NA	NA
		0.063	D	D	-
		0.040	NA	D	-
2" to 3" included	1.4	0.315	D	NA	NA
3" to 4" included	2.3	0.380	D	NA	NA
4" to 5" included	3.0	0.440	D	NA	NA
5" to 6" included	4.1	0.500	D	NA	NA

TABLE 13. STANDARD MANUFACTURING LIMITS FOR SOLID SHAPES FORMED FROM BERYLLIUM ALLOYS

Circumscribing Circle Diameter, in.	Minimum Cross Sectional Area, in^2	Minimum Section Thickness, inch	Manufacturing Capability[1]		
			Extruded	Extruded and Drawn	Form Rolled
Up to 1" included	0.06	0.040	B	NA	NA
1" to 1.375" included	0.15	0.100	B	-	NA
	0.08	0.060	B	B	NA
	0.06	0.040	NA	B	NA
1.375" to 2" included	0.31	0.125	B	-	NA
	-	0.060	B	B	NA
	-	0.040	NA	B	NA
2" to 3" included	0.5	0.125	B	NA	NA
	-	0.090	B	NA	NA

SECTION 2

TOLERANCES AND DESIGN CRITERIA

by

Gerald A. Gegel

Page

SECTION 2

TOLERANCES AND DESIGN CRITERIA

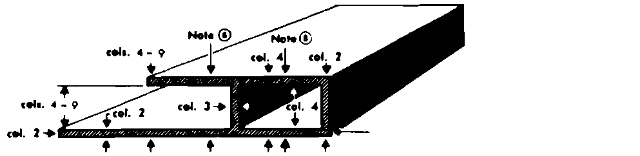
Most extruded, drawn, or form-rolled structural shapes currently produced are basic angle, tee, or channel shapes or combinations of these shapes. The dimensional tolerances to which these products can be formed are a function of the capabilities of the forming process and the material being formed. This section of the Guide contains typical dimensional tolerances that can be provided, on a production basis, by extrusion or roll forming.

In addition, certain manufacturing limitations such as corner and fillet radii and geometric limitations are also listed. The data for extruded products are categorized in the same manner as the availability data presented in Section 1 and are contained in Tables 14 through 18.

The geometric limitations dictated by the primary fabrication process are not the only fabrication parameters that must be considered by the designer. In all cases, the designer must consider the effects of heat treatment on mechanical and physical properties, whether or not secondary fabrication operations such as hot straightening or joggling will adversely affect properties or service life, the necessity of removing the alpha-case from titanium alloys, etc. For more information on these and other limitations, the reader is referred to Technical Memorandum MAA70-7, "Air Force Systems Requirements for Materials and Processes", September, 1970.

TABLE 14. TOLERANCES AND GEOMETRIC LIMITATIONS: ALUMINUM ALLOYS*

A. Dimensional(1)



Specified dimension, inches	Tolerance — Inches plus and minus: Metal dimensions — Allowable deviation from specified dimension where 75 per cent or more of the dimension is metal: All Except those covered by column 3		Wall thickness completely enclosing space 0.11 sq. in. and over (eccentricity)		Space dimensions — Allowable deviation from specified dimension where more than 25 per cent of the dimension is space: At dimensioned points 0.250-0.624 inches from base of leg		At dimensioned points 0.625-1.249 inches from base of leg		At dimensioned points 1.250-2.499 inches from base of leg		At dimensioned points 2.500-3.999 inches from base of leg		At dimensioned points 4.000-5.999 inches from base of leg		At dimensioned points 6.000-8.000 inches from base of leg	
Col. 1	Col. 2		Col. 3		Col. 4		Col. 5		Col. 6		Col. 7		Col. 8		Col. 9	
	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys	Alloys 5083, 5086, 5456	Other Alloys
CIRCUMSCRIBING CIRCLE SIZES LESS THAN 10 INCHES IN DIAMETER																
Up thru 0.124	0.009	0.006	±15% of specified dimension; ±0.090 max. ±0.015 min.	±10% of specified dimension; ±0.060 max. ±0.010 min.	0.013	0.010	0.015	0.012								
0.125- 0.249	0.011	0.007			0.016	0.012	0.018	0.014	0.020	0.016						
0.250- 0.499	0.012	0.008			0.018	0.014	0.020	0.016	0.022	0.018	0.024	0.020				
0.500- 0.749	0.014	0.009			0.021	0.016	0.023	0.018	0.025	0.020	0.027	0.022				
0.750- 0.999	0.015	0.010			0.023	0.018	0.025	0.020	0.027	0.022	0.030	0.025	0.035	0.030		
1.000- 1.499	0.018	0.012			0.027	0.021	0.029	0.023	0.032	0.026	0.036	0.030	0.041	0.035		
1.500- 1.999	0.021	0.014			0.031	0.024	0.033	0.026	0.038	0.031	0.043	0.036	0.019	0.042	0.057	0.050
2.000- 3.999	0.036	0.024			0.046	0.034	0.050	0.038	0.060	0.048	0.069	0.057	0.080	0.068	0.092	0.080
4.000- 5.999	0.051	0.034			0.061	0.044	0.067	0.050	0.081	0.064	0.095	0.078	0.111	0.094	0.127	0.110
6.000- 7.999	0.066	0.044			0.076	0.054	0.084	0.062	0.104	0.082	0.121	0.099	0.142	0.120	0.162	0.140
8.000- 9.999	0.081	0.054			0.091	0.064	0.101	0.074	0.127	0.100	0.147	0.120	0.182	0.145	0.197	0.170
CIRCUMSCRIBING CIRCLE SIZES 10 INCHES IN DIAMETER AND OVER																
Up thru 0.124	0.021	0.014	±15% of specified dimension; ±0.090 max. ±0.025 min.	±15% of specified dimension; ±0.090 max. ±0.015 min.	0.025	0.018	0.027	0.020								
0.125- 0.249	0.022	0.015			0.026	0.019	0.029	0.022	0.035	0.028						
0.250- 0.499	0.024	0.016			0.028	0.020	0.032	0.024	0.038	0.030	0.058	0.050				
0.500- 0.749	0.025	0.017			0.030	0.022	0.035	0.027	0.049	0.040	0.068	0.060				
0.750- 0.999	0.027	0.018			0.031	0.023	0.039	0.030	0.057	0.050	0.079	0.070	0.099	0.090		
1.000- 1.499	0.028	0.019			0.033	0.024	0.043	0.034	0.069	0.060	0.089	0.080	0.109	0.100		
1.500- 1.999	0.036	0.024			0.046	0.034	0.056	0.044	0.082	0.070	0.102	0.090	0.122	0.110	0.182	0.170
2.000- 3.999	0.051	0.034			0.061	0.044	0.071	0.054	0.097	0.080	0.117	0.100	0.137	0.120	0.197	0.180
4.000- 5.999	0.066	0.044			0.076	0.054	0.086	0.064	0.112	0.090	0.132	0.110	0.152	0.130	0.212	0.190
6.000- 7.999	0.081	0.054			0.091	0.064	0.101	0.074	0.127	0.100	0.147	0.120	0.167	0.140	0.227	0.200
8.000- 9.999	0.096	0.064			0.106	0.074	0.116	0.084	0.142	0.110	0.162	0.130	0.182	0.150	0.242	0.210
10.000-11.999	0.111	0.074			0.121	0.084	0.131	0.094	0.157	0.120	0.177	0.140	0.197	0.160	0.257	0.220
12.000-13.999	0.126	0.084			0.136	0.094	0.146	0.104	0.172	0.130	0.192	0.150	0.212	0.170	0.272	0.230
14.000-15.999	0.141	0.094			0.151	0.101	0.161	0.114	0.187	0.140	0.207	0.160	0.227	0.180	0.287	0.240
16.000-17.999	0.156	0.104			0.166	0.114	0.176	0.124	0.202	0.150	0.222	0.170	0.242	0.190	0.302	0.250
18.000-19.999	0.171	0.114			0.181	0.124	0.191	0.134	0.217	0.160	0.237	0.180	0.257	0.200	0.317	0.260
20.000-21.999	0.186	0.124			0.196	0.131	0.206	0.141	0.232	0.170	0.252	0.190	0.272	0.210	0.332	0.270
22.000-24.000	0.201	0.134			0.211	0.144	0.221	0.151	0.247	0.180	0.267	0.200	0.287	0.220	0.347	0.280

*Aluminum Standards & Data, 1972-73, published by Aluminum Association.

Table 14. (Continued)

(1) These Standard Tolerances are applicable to the average shape; wider tolerances may be required for some shapes and closer tolerances may be possible for others.

(2) The tolerances applicable to a dimension composed of two or more component dimensions is the sum of the tolerances of the component dimensions if all of the component dimensions are indicated.

(3) When a dimension tolerance is specified other than as an equal bilateral tolerance, the value of the Standard Tolerance is that which would apply to the mean of the maximum and minimum dimensions permissible under the tolerance.

(4) Where dimensions specified are outside and inside, rather than wall thickness itself, the allowable deviation (eccentricity) given in Column 3 applies to mean wall thickness. (Mean wall thickness is the average of two wall thickness measurements taken at opposite sides of the void.)

(5) In the case of Class 1 Hollow Shapes the standard wall thickness tolerance for extruded round tube is applicable. (A Class 1 Hollow Shape is one whose void is round and one inch or more in diameter and whose weight is equally distributed on opposite sides of two or more equally spaced axes.)

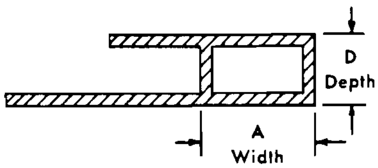
(6) At points less than 0.250 inch from base of leg the tolerances in Col. 2 are applicable.

(7) Tolerances for extruded shapes in -T3510, -T4510, -T6510 and -T8510 tempers shall be subject to special inquiry.

(8) The following tolerances apply where the space is completely enclosed (hollow shapes):

For the width (dimension A) the tolerance is the value shown in Column 4 for the depth (dimension D).

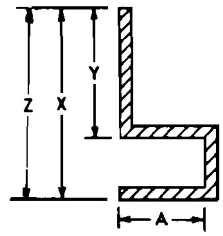
For the depth (dimension D) the tolerance is the value shown in Column 4 for the width (dimension A).

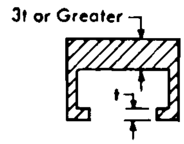


In no case is the tolerance for either width or depth less than at the corners (Column 2, metal dimensions).

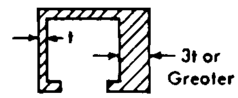
Example—Hollow shape having 1 x 3 inch rectangular outside dimensions: width tolerance is ±0.021 inch and depth tolerance ±0.034 inch. (Tolerances at corners, Column 2, metal dimensions, are ±0.024 inch for the width and ±0.012 inch for the depth.) Note that the Col. 4 tolerance of 0.021 inch must be adjusted to 0.024 inch so that it is not less than the Col. 2 tolerance.

(9) These tolerances do not apply to space dimensions such as dimensions "X" and "Z" of the example (right) even when "Y" is 75 percent or more of "X." For the tolerance applicable to dimensions "X" and "Z," use Col. 4, 5, 6, 7, 8 or 9, dependent on distance "A."

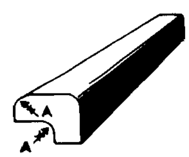




(10) Tolerance applicable to the wall thickness enclosing the void of hollow and semihollow shapes is subject to special inquiry when the nominal thickness of one wall is three times or greater than that of the opposite wall.



B. Corners and Fillets

Specified radius inches	Tolerances, inches — Allowable deviation from specified radius  Difference between radius A and specified radius
Sharp corners	+1/64
Under 0.188	±1/64
0.188 and over	±10%

C. Lengths(1)

ROD, BAR AND SHAPES

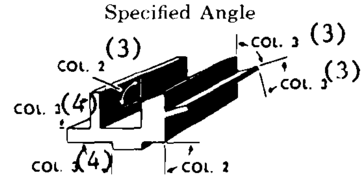
Circumscribing circle diameter (shapes); specified diameter (rod); specified width (bar) inches	Tolerance—Inches plus			
	Allowable deviation from specified length			
	Specified length—Feet			
	Up thru 12	Over 12 thru 30	Over 30 thru 50	Over 50
Under 3.000	+1/8	+1/4	+3/8	+1
3.000-7.999	+3/16	+5/16	+7/16	+1
8.000 and over	+1/4	+3/8	+1/2	+1

(1) Tolerances for 0, T3510, T4510, T6510, T73510, T76510, and T8510 tempers shall be at time of purchase.

Squareness of cut ends: ±1 degree

Table 14. (Continued)

D. Angles[1,2]

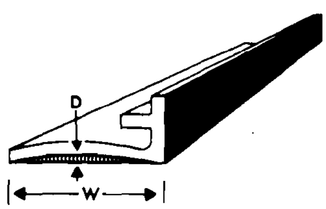


Minimum Specified Leg thickness inches	Tolerence Degrees plus and minus Allowable deviation from Specified Angle Ratio (3,4) Leg or surface length To leg or metal thickness 1 and less	 Over 1
Col. 1	Col 2	Col. 3
Under 0.188	1	2
0.188-0.749	1	1½
0.750 and over	1	1

(1) Angles are measured with protractors or gauges. A four-point contact system is used, two contact points being as close to the angle vertex as practical, and the others near the ends of the respective surfaces forming the angle.
(2) Not applicable to extruded shapes in -0, -T3510, -T4510, -T6510, or -T8510 tempers.
(3) When the space between the surfaces forming an angle is all metal, values in column 2 apply if the larger surface length to metal thickness ratio is 1 or less.
(4) When two legs are involved the one having the larger ratio determines the applicable column.

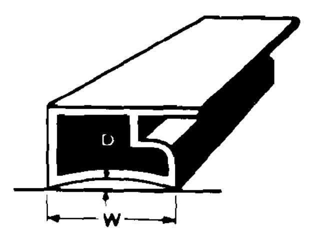
E. Transverse Flatness[1]

Solid and Semihollow Shapes



Surface width inches	Tolerance—Inches Maximum allowable deviation D
Up thru 1	0.004
Over 1	0.004 x W (inches)
In any 1 in. of width	0.004

Hollow Shapes



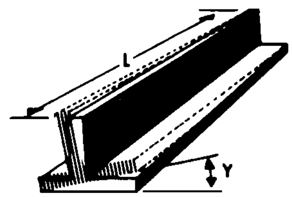
Minimum Thickness of metal forming the surface inches	Tolerance, inches Maximum allowable deviation D Widths up thru 1 in. or any 1 in. increment of wider surfaces	 Widths Over 1 in.
Under 0.188	0.006	0.006 x W (inches)
0.188 and over	0.004	0.004 x W (inches)

(1) Not applicable to extruded shapes in -0, -T3510, -T4510, -T6510, or -T8510 tempers. Tolerances for extruded shapes in these tempers are subject to special inquiry.

Table 14. (Continued)

F. Twist[1]

Shapes

Temper	circumscribing circle diameter inches	Specified thickness (rectangles); minimum thickness (shapes) inches	Tolerance—Degrees Allowable deviation from straight  Y (max) in degrees	
			In any foot or less of length	In total length of piece
All except -O, -TX510, -TX511[2]	Up thru 1.499 1.500-2.999 3.000 and over	All All All	1 ½ ¼	1 x length, ft; 7° max ½ x length, ft; 5° max ¼ x length, ft; 3° max
-TX510 [2]	0.500 and over	0.095 and over	[3]	[3]
-TX511[2]	0.500-1.499 1.500-2.999 3.000 and over	0.095 and over 0.095 and over 0.095 and over	1 ½ ¼	1 x length, ft; 7° max ½ x length, ft; 5° max ¼ x length, ft; 3° max

(1) Twist is normally measured by placing the extruded section on a flat surface and measuring the maximum distance of any point along its length between the bottom surface of the section and the flat surface. From this measurement, the deviation from true straightness of the section is subtracted. The remainder is the twist. To convert the standard twist tolerance (degrees) to an equivalent linear value, the tangent of the standard tolerance is multiplied by the width of the surface of the section that is on the flat surface.

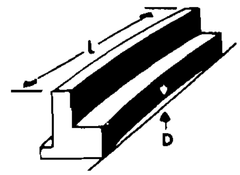
(2) -TX510 and -TX511 are general designations for the following stress-relieved tempers: -T3510, -T4510, -T6510, -T8510, and -T3511, -T4511, -T6511, -T8511, respectively.

(3) Not applicable to extruded shapes in -T3510, -T4510, -T6510 or -T8510 tempers. Tolerances for extruded shapes in these tempers are subject to special inquiry.

Table 14. (Continued)

G. Camber

Straightness

Product	Temper	Specified diameter (rod); Specified width (bar); circumscribing circle diameter (3) (shapes) inches	Specified thickness (rectangles); minimum thickness (shapes) inches	Tolerance (2)—Inches Allowable deviation (D) from straight 	
				In any foot or less of length	In total length of piece
Rod and Square and Hexagonal Bar	All except -O, -TX510, -TX511 (1)	All	....	0.0125	0.0125 x length, ft
	-TX510 (1)	0.500 and over	....	0.050	0.050 x length, ft
	-TX511 (1)	0.500 and over	....	0.0125	0.0125 x length, ft
Rectangular Bar	All except -O, -TX510, -TX511 (1)	Up thru 1.499	Up thru 0.094 0.095 and over	0.050 0.0125	0.050 x length, ft 0.0125 x length, ft
		1.500 and over	All	0.0125	0.0125 x length, ft
	-TX510 (1)	Over 0.500	0.500 and over	0.050	0.050 x length, ft
	-TX511 (1)	Over 0.500	0.500 and over	0.0125	0.0125 x length, ft
Shapes	All except -O, -TX510, -TX511 (1)	Up thru 1.499	Up thru 0.094 0.095 and over	0.050 0.0125	0.050 x length, ft 0.0125 x length, ft
		1.500 and over	All	0.0125	0.0125 x length, ft
	-TX510 (1)	0.500 and over	0.095 and over	(2)	(2)
	-TX511 (1)	0.500 and over	0.095 and over	0.0125	0.0125 x length, ft

(1) -TX510 and -TX511 are general designations for the following stress-relieved tempers: -T3510, -T4510, -T6510, -T8510, and -T3511, -T4511, -T6511, -T8511, respectively.
(2) When weight of piece on flat surface minimizes deviation.
(3) The circumscribing circle diameter is the diameter of the smallest circle that will completely enclose the shape.
(4) Not applicable to extruded shapes in -T3510, -T4510, -T6510 or -T8510 tempers. Tolerances for extruded shapes in these tempers are subject to special inquiry.

H. Surface Finish

Specified Section thickness inches	Allowable depth of defects (1) inches Maximum
Under 0.064	0.0015
0.064-0.125	0.002
0.126-0.188	0.0025
0.189-0.250	0.003
0.251-0.500	0.004
0.501 and over	0.008

(1) Defects include die lines and handling marks.

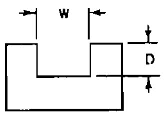
I. Leg Length — Section Thickness Ratio

14:1 maximum

Table 14. (Continued)

J. Tongue Ratio, D/W

D/W = 1/1



K. Circumscribing Circle

This is the diameter of the smallest circle that will completely enclose the cross section of the shape. The maximum circumscribing diameter is 24 inches.

L. The minimum web thickness available is 0.040 inch.

TABLE 15. TOLERANCES AND GEOMETRIC LIMITATIONS: CARBON AND ALLOY STEEL EXTRUSION

A. Dimensional:

Ordered Dimension	Tolerances, in. Regular Extrusion	Made on 12,000 Ton USAF Extrusion Press	
Under 1" included	±0.020	+0.060	–0.010
1" – 3" included	±0.030	–	
1" – 1-1/2" included	–	+0.090	–0.010
1-1/2" – 2" included	–	+0.120	–0.010
2" – 5" included	–	+0.150	–0.010
3" – 5-1/2" included	±0.040	–	
5-1/2" – 9" included	±0.062	+0.200	–0.060
9" – 12" included	–	+0.200	–0.060
Over 12"		+0.250	–0.060

B. Corners and Fillets:

	Regular Extrusion	Made on 12,000 Ton USAF Extrusion Press
Fillets	0.187 ± 0.062	0.500 ± 0.125"
Corners	0.062 ± 0.032	0.250 ± 0.062"

C. Lengths:

Random lengths: permissible variation is up to 24 inches with 10 percent shorts down to 5 feet.

Multiple lengths: 1/4-inch is added to the total length of each piece for each multiple contained, unless otherwise specified.

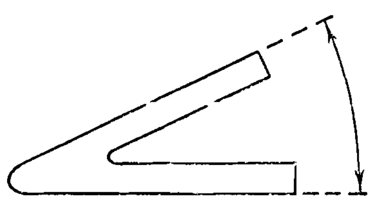
Exact or dead lengths: Tolerances

	Permitted Variation Over	Under
Lengths under 12 feet	3/16"	0
Lengths 12 feet and over	1/4"	0

Ends out of square: 0.017 inch per inch of cut.

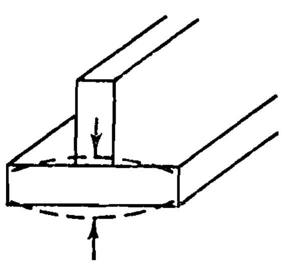
D. Angles:

± 2 degrees



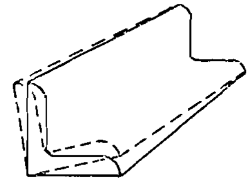
E. Transverse Flatness:

±0.010 inch per inch of width; 0.010 inch minimum



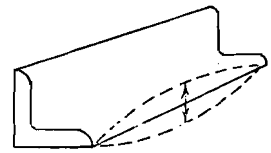
F. Twist:

Section Width	Rise In, 5 feet
0"–4" included	0.125"
4"–9" included	0.188"



G. Camber (Straightness):

Deviation from staightness will not exceed 0.125" in any 5 foot length.



H. Surface Finish:

Surface finishes of 250 RMS maximum are commonly delivered, but this is not normally measured.

I. Surface Defects:

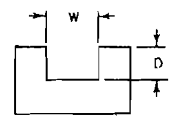
Occasional surface defects such as laps and seams occur during extrusion. These defects shall be capable of being removed by localized grinding or machining to not less than the minimum drawing dimension in the area of occurrence.

J. Leg Length – Section Thickness Ratio

14:1 maximum

K. Tongue Ratio, D/W

D/W = 1/1



L. Circumscribing Circle

This is the diameter of the smallest circle that will completely enclose the cross section of the shape. The maximum circumscribing diameter is 20.5 inches.

M. The minimum web thickness is 0.125 inches.

TABLE 16. TOLERANCES AND GEOMETRIC LIMITATIONS: STAINLESS STEEL EXTRUSIONS

A. Dimensional:

Ordered Dimension	Tolerances, in. Regular Extrusion	Made on 12,000 Ton USAF Extrusion Press	
Under 1" included	±0.020	+0.060	−0.010
1" − 3" included	±0.030	−	
1" − 1-1/2" included	−	+0.090	−0.010
1-1/2" − 2" included	−	+0.120	−0.010
2" − 5" included	−	+0.150	−0.010
3" − 5-1/2" included	±0.040	−	
5-1/2" − 9" included	±0.062	+0.200	−0.060
9" − 12" included	−	+0.200	−0.060
Over 12"	−	+0.250	−0.060

B. Corners and Fillets:

	Regular Extrusion	Made on 12,000 Ton USAF Extrusion Press
Fillets	0.187 ± 0.062"	0.500 ± 0.125"
Corners	0.062 ± 0.032"	0.250 ± 0.062"

C. Lengths:

Straightened lengths up to 60 feet*. Deglassed and heat treated lengths to 40 feet.

Random lengths: permissible variation is up to 24 inches with 10 percent shorts down to 5 feet.

Multiple lengths: 1/4-inch is added to the total length of each piece for each multiple contained, unless otherwise specified.

Exact or dead lengths: Tolerances

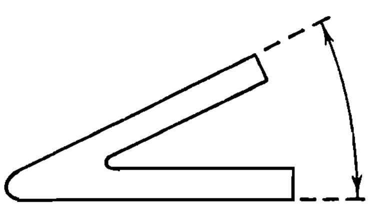
	Permitted Variation Over	Under
Lengths under 12 feet	3/16"	0
Lengths 12 feet and over	1/4"	0

Ends out of square: 0.017 inch per inch of cut.

*Maximum lengths may be adversely affected by one or more factors, including cross section of shape, alloy, annealing procedure, pickling, stretch straightening, need for heat treatment.

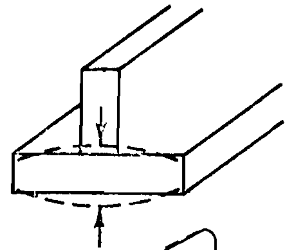
D. Angles:

± 2 degrees



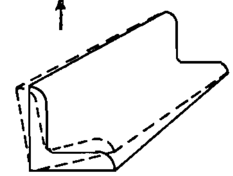
E. Transverse Flatness:

±0.010 inch per inch of width: 0.010 inch minimum



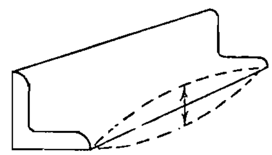
F. Twist:

Section Width	Rise In, 5 feet
0"– 4" included	0.125"
4"–9" included	0.188"



G. Camber (Straightness):

Deviation from straightness will not exceed 0.125 inch in any 5 feet length.



H. Surface finish:

Surface finishes of 250 RMS maximum are commonly delivered.

I. Surface defects:

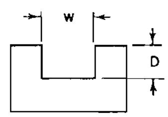
Occasional surface defects such as laps and seams occur during extrusion. These defects shall be capable of being removed by localized grinding or machining to not less than the minimum drawing dimension in the area of occurrence.

J. Leg Length – Section Thickness Ratio

8:1 maximum

K. Tongue Ratio, D/W

D/W ⩽ 1



L. Circumscribing Circle

This is the diameter of the smallest circle that will completely enclose the cross section of the shape. The maximum circumscribing diameter is 20.5 inches.

M. The minimum web thickness available is 0.125 inch.

TABLE 17. TOLERANCES AND GEOMETRIC LIMITATIONS: TITANIUM ALLOYS

A. Dimensional:

Ordered Dimension	Tolerances: Regular Extrusion	Tolerances: Close Tolerance Extrusion	Tolerances: Made on 12,000 Ton USAF Extrusion Press	
0 – 1" included	±0.020	±0.015	+ 0.060	–0.010
1 – 2" included	±0.030	±0.020	+0.120	–0.010
2 – 3" included	±0.040	±0.030	+0.150	–0.010
Over 3"	±0.062	–	–	
3 – 5" included	–	–	+0.150	–0.010
5 – 12" included	–	–	+0.200	–0.060
Over 12"	–	–	+0.250	–0.060

B. Corners and Fillets:

	Regular Extrusion	Close Tolerance Extrusion	Made on 12,000 Ton USAF Extrusion Press
Fillets	0.187" ± 0.050"	0.031 ± 0.031"	0.500 ± 0.125"
Corners	0.093" ± 0.025"	0.031 ± 0.031"	0.250 ± 0.062"

C. Lengths:

Maximum length*

	Regular Extrusion	Close Tolerance Extrusion
Annealed Temper	60 feet	33 feet
STA Temper	30 feet	27-1/2 feet

Random lengths: permissible variation is up to 24 inches with 10 percent shorts down to 5 feet.

Multiple lengths: 1/4-inch is added to the total length of each piece for each multiple contained, unless otherwise specified.

Exact or dead lengths: Tolerances

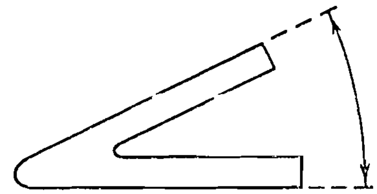
	Permitted Variation: Over	Permitted Variation: Under
Lengths under 12 feet	3/16"	0
Lengths 12 feet and over	1/4"	0

Ends out of square: 0.017-inch per inch of cut.

*Maximum length may be adversely affected by one or more factors, including cross section of shape, alloy, annealing procedure, pickling, stretch straightening, need for heat treatment.

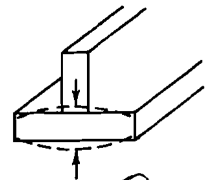
D. Angles:

± 2 degrees



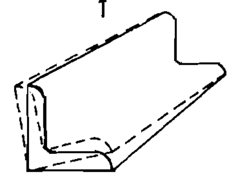
E. Transverse Flatness:

±0.010-inch per inch of width; 0.010 inch minimum.



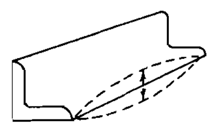
F. Twist

1 degree per foot of length, 5 degrees maximum in a full length.



G. Camber (Straightness):

Deviation from straightness will not exceed 0.125 inch in any 5 foot length when the weight of the part and pressure not to exceed 200 pounds are used to minimize bow.



H. Surface Finish:

Surface finishes of 225 RMS are commonly delivered but this is not normally measured. Chem-milled material has a substantially improved surface finish.

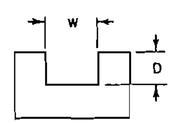
I. Surface Defects:

Occasional surface defects such as laps and seams occur during extrusion. These defects shall be capable of being removed by localized grinding or machining to not less than the minimum drawing dimension in the area of occurrence.

J. Leg Length – Section Thickness Ratio:

12:1 maximum

K. Tongue Ratio, D/W



D/W ⩽ 1/1

L. Circumscribing Circle:

The maximum circumscribing circle diameter is 20-1/2 inches.

M. The minimum web thickness is 0.125 inch for a standard commercial extrusion practice.

NOTE: In general, titanium extrusions must be machined to remove the alpha case formed during processing and to remove surface imperfections. The amount of material to be removed is normally about 0.050-inch per surface. Experience at several aircraft companies indicates that if net sections are to be machined from extrusions the following tolerances are necessary on the as-extruded shapes from the supplier:

Angles: ± 1 degree
Twist: 1/4 degree per foot of length, 3 degrees maximum in a full length
Camber: Deviation from straightness will not exceed 0.012 inch times total length in feet.

It is particularly important to obtain these tolerances on heavy section extrusions because of their increased resistance to straightening.

The above tolerances may be obtained but additional costs will be incurred due to the necessity of developing specialized handling and extrusion practices for each particular shape or family of shapes.

TABLE 18. TOLERANCES AND GEOMETRIC LIMITATIONS: Ni-BASE ALLOY EXTRUSIONS

A. Dimensional:

Ordered Dimension	Tolerances: Regular Extrusion	Tolerances: Made on 12,000 Ton USAF Extrusion Press	
Under 1" included	±0.020	+0.060	–0.010
1" – 1-1/2" included	–	+0.090	–0.010
1-1/2" – 2" included	–	+0.120	–0.010
1" – 3" included	±0.031	–	–
2" – 3" included	–	+0.150	–0.010
3" – 4-1/2" included	±0.046	–	
3" – 5" included	–	+0.150	–0.010
5" – 12" included	–	+0.200	–0.060
Over 12"	–	+0.250	–0.060

B. Corners and Fillets:

	Normal Production	Made on 12,000 Ton USAF Extrusion Press
Fillets	0.250 ± 0.032"	0.500 ± 0.125"
Corners	0.062 ± 0.032"	0.250 ± 0.062"

C. Lengths:

Maximum length*: 60 feet

Random lengths: permissible variations is up to 25 inches.

Multiple lengths: 1/4 inch is added to the total length of each piece for each multiple contained, unless otherwise specified.

Exact or dead lengths: Tolerances

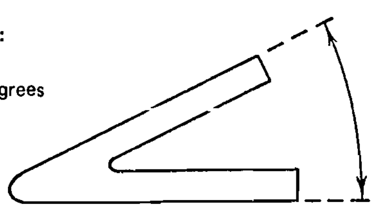
	Permitted Variation: Over	Permitted Variation: Under
Lengths under 12 feet	3/16"	0
Lengths 12 feet and over	1/4"	0

Ends out of square: 0.017-inch per inch of cut.

*Maximum lengths may be adversely affected by one or more factors, including cross section fo shape, alloy, annealing procedure, pickling, stretch straightening, need for heat treatment.

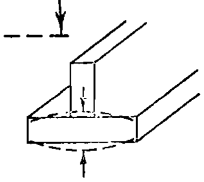
D. Angles:

± 2 degrees



E. Transverse Flatness:

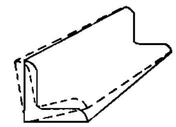
±0.010-inch per inch of width: 0.010-inch minimum.



F. Twist:

Section Width	Rise In 5 feet
1/2" – 1-1/2" included	0.125"
1-1/2" – 5" included	0.188"

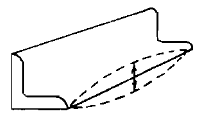
Not to exceed: $\frac{\text{No. of feet in length}}{5}$



G. Camber (Straightness):

Deviation from straightness will not exceed 0.125 inch in any 5 feet length, but not to exceed

$$(0.125)\ \frac{\text{No. of feet in length}}{5}$$



H. Surface Finish:

Surface finishes of 250 RMS maximum are commonly delivered, but this is not normally measured.

I. Surface Defects:

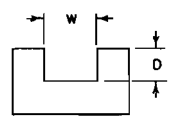
Occasional surface defects such as laps and seams occur during extrusion. These defects shall be capable of being removed by localized grinding or machining to not less than the minimum drawing dimension in the area of occurrence.

J. Leg Length – Section Thickness Ratio

12:1 maximum

K. Tongue Ratio, D/W

Normally $\frac{D}{W} \leqslant 1$



L. Circumscribing Circle:

L. Circumscribing Circle:

This is the diameter of the smallest circle that will completely enclose the cross-section of the shape. The maximum circumscribing diameter is 20-1/2 inches.

M. The minimum web thickness is 0.500-inch.

TABLE 19. TOLERANCES AND GEOMETRIC LIMITATIONS: ROLL FORMED SHAPES

A. Dimensional:

Dimensional Feature	Tolerance, in.
Contour	±0.001 to ±0.005
Thickness	±0.002 to ±0.005
Width	±0.005 to ±0.015

B. Corners and Fillets:

Fillets:

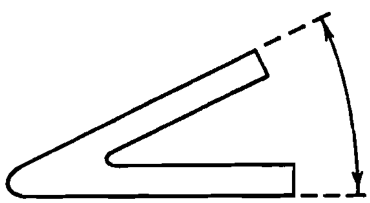
Corners:

C. Lengths:

Maximum length of 25 feet. This limitation is imposed by available streightening and heat treating equipment.

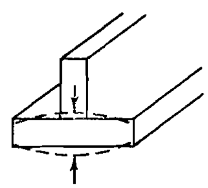
D. Angles:

± 2 degrees



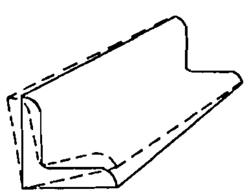
E. Transverse Flatness:

Maximum of ±0.005 inch per inch of cross section width.



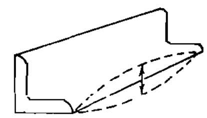
F. Twist:

As rolled: $\pm 5^{\circ}$ per foot
As stretch straightened:
$\pm 1^{\circ}$ per foot



G. Camber (Straightness)

As rolled: 0.150 in. per foot
As stretch straightened:
0.025 in. per foot.



H. Surface Finish:

Surface finishes of 5 to 30 microinches RMS in the as-rolled condition. As deburred, the edges will have surface finishes of 30 to 60 microinches RMS.

I. Circumscribing Circle:

This is the diameter of the smallest circle that will completely enclose the cross section of the shape. Present equipment capabilities limit this to a diameter of 3 inches.

J. The minimum section thicknesses available are:

Stainless Steels:	0.030 inch
Low Carbon alloy steels:	0.030 inch
Titanium alloys:	0.060 inch
Superalloys:	0.040 inch

SECTION 3

DESIGN PROPERTY DATA FOR STRUCTURAL SHAPES AND TUBING

by

E. G. Smith, Jr.
D. E. Nichols

SECTION 3

DESIGN PROPERTY DATA FOR STRUCTURAL SHAPES AND TUBING

This section is a compilation of design property data for selected materials in the form of structural shapes and seamless tubing. These forms may be produced by one or more of several fabrication processes including extrusion, drawing, form rolling, and tube reducing. After processing, these products are normally straightened and then heat treated to impart the best combination of properties for a particular application. Design data are then developed for the processed and heat-treated materials, since shapes and tubing are used most often in this condition.

The data presented in this Section came from the open literature. It is intended that this Section of the Guide serve as a convenient reference for property data and guide the designer of aerospace components in evaluating candidate materials for applications that require structural shape and tubing forms.

The materials included in this Section are divided into the following six categories:

Aluminum	Superalloys
Titanium	Refractory Metals
Steels	Beryllium

Selection of specific alloys for each category was based on discussions with personnel from various aerospace companies, fabrication houses, and metal producers. Many of these alloys have been and are currently being used extensively for aerospace applications; in general these alloys are commercially available as shapes and tubing. Other alloys that have been included have not been widely used to date or have been used primarily for nonaerospace applications. The commercial availability of these alloys is limited and usually on an experimental basis.

A wide variation was found in the amount of suitable data available for the six material categories. As might be expected, the greatest amount of data was compiled for the aluminum and titanium alloys, since more extensive use has been made of these materials as structural shapes and tubing in aircraft applications. In contrast, the available data for the other four categories were sparse and rather fragmentary.

The data compiled include physical and mechanical properties as well as limited data for creep, stress rupture, and fatigue. A comparison of these properties for various alloys in a particular category is limited to physical and elastic properties. Such data are presented at the beginning of each material category. Data for individual alloys follow any comparative data with mechanical properties being tabulated in a format similar to that used in design handbooks.

An effort has been made in this Section to prevent unnecessary duplication of information in existing design handbooks. However, for the sake of continuity, ranges of statistical design allowables (A and B values) as well as proposed specification (S values) and minimum values from various handbooks have been condensed and included for those alloys for which such data have been established. These condensed values appear at the beginning of the data presentation for individual alloys. Following these handbook values are typical test data taken from specific sources for material and test conditions not covered by the handbook data. These test data are also presented as ranges to indicate the extreme values obtained for the various properties. Plotted curves are used to present most of the variations in property data with temperature as well as all creep, stress rupture, and fatigue data.

Fracture toughness or more correctly, stress intensity, has become an important property in recent years for designing aerospace components with specified useful lifetimes. During the preparation of this Section, fracture-toughness data were compiled for several alloys in the aluminum and titanium categories. However, these data have not been included in the Design Guide because testing conditions, specimen design, etc., were not clearly defined in many of the data sources, and it was not always clear whether the fracture toughness data represented valid plane-strain (K_{IC} and K_{ISCC}), plane-stress (K_C and K_{SCC}), or provisional stress (K_Q) values. Rather than present data that could be misleading, attention is directed to a recent Handbook* devoted entirely to fracture toughness and related crack-growth properties. A soon-to-be-published revision of this Handbook will contain a considerable amount of new data for extruded shapes. More importantly, data in this Handbook have been analyzed thoroughly and their validity verified, clearly indicating the particular type of testing conditions and fracture toughness values they represent.

A glossary of symbols and other abbreviations that appear in the tables and figures of Section 3 have been summarized in Table 20. Also included are definitions explaining the meaning of these as they are used in this Section.

**Damage Tolerance Design Handbook*, MCIC-HB-01, Published by the Metals and Ceramics Information Center, Battelle Columbus Laboratories, Columbus, Ohio, December, 1972.

TABLE 20. GLOSSARY OF SYMBOLS AND ABBREVIATIONS USED IN SECTION 3

Symbol	Definition
F_{tu}	Ultimate tensile stress
F_{ty}	Tensile yield stress
F_{cy}	Compressive yield stress
F_{su}	Ultimate shear stress
F_{bru}	Ultimate bearing stress
F_{bry}	Bearing yield stress
e	Tensile elongation
E	Modulus of elasticity in tension
E_c	Modulus of elasticity in compression
G	Modulus of rigidity in shear
μ	Poisson's ratio
ω	Density
C	Heat capacity
K	Thermal conductivity
α	Mean thermal expansion coefficient
L	Longitudinal grain direction
LT	Long-transverse grain direction
ST	Short-transverse grain direction
e/D	Ratio of hole centerline-edge distance to pin diameter in bearing test
R	Ratio of minimum to maximum stress in fatigue test
K_t	Ratio of actual to nominal stress in fatigue test
N	Number of stress reversals or cycles in fatigue test
A	Minimum statistical design value based on >99 percent probability and 95 percent confidence limit
B	Minimum statistical design value based on >90 percent probability and 95 percent confidence limit
S	Minimum specified or recommended value
AC	Air-cooled
WQ	Water-quenched
OQ	Oil-quenched
ksi	1000 pounds per square inch
cpm	Cycles per minute
w/o	Weight percent
NG	Not given

ALUMINUM

ALUMINUM DATA SOURCES

(1) "Metallic Materials and Elements for Aerospace Vehicle Structures", Military Standardization Handbook (MIL-HDBK-5B) September, 19771.

(2) "Aluminum Standards and Data", The Aluminum Association, Third Edition, January, 1972.

(3) "Aerospace Structural Metals Handbook – Non-Ferrous, Ligh-Metal Alloys", Volume II (Fourth Revision), Syracuse University Press, Syracuse, N.Y. March, 1967.

(4) "Plane Strain Fracture Toughness Data for Selected Metals and Alloy", DMIC Report S-28, June, 1969.

(5) Kaufman, J. G., et al., "Fracture Toughness, Fatigue, and Corrosion Characteristics of X7080-T7E41 and 7178-T651 Plate and 7075-T6510, 7075-T73510, X7080-T7E42, and 7178-T6510 Extruded Shapes", AFML-TR-69-225, November, 1969.

(6) Kaufman, J. G., et al., "New Data on Moduli of Elasticity of Aluminum Alloys", Alcoa Research Laboratories, ARL No. 9-70-27, August 3, 1970.

(7) "Alcoa Alloy 2219", Alcoa Green Letter, 1971.

(8) Private communication from Alcoa to Battelle.

(9) "Alcoa Alloy 7005", Alcoa Green Letter, 1968.

(10) Jones, R. E. "Mechanical Properties of 7049-T73 and 7049-T76 Aluminum Alloy Extrusions at Several Temperatures", AFML-TR-72-2, February, 1972.

(11) "Engineering Data on New Aerospace Structural Materials", AFML-TR-72-196, Volume II, September, 1972.

(12) "Alcoa Alloy 7050", Alcoa Green Letter, 1973.

(13) "Alcoa Alloys 7075-T76 and 7178-T76", Alcoa Green Letter, January, 1972.

(14) Sidwell, D. R., "Mechanical Properties of 7075-T76510 Aluminum Alloy Extrusions", Lockheed California Report No. LR-23693, June 18, 1970.

(15) "Damage Tolerant Design Handbook" (MCIC-HB-01), Metals and Ceramics Information Center, Battelle's Columbus Laboratories, Columbus, Ohio, December 1972.

TABLE 21. SUMMARY OF ROOM TEMPERATURE ELASTIC AND PHYSICAL PROPERTY DATA FOR ALUMINUM ALLOYS

(Source 1, 2, 3)

Property	Range of Values	Property	Range of Values
Elastic		Physical	
$E - 10^6$ psi	9.9 – 10.8	ω – lb/in^3	0.096 – 0.102
$E_c - 10^6$ psi	10.1 – 11.0	C – Btu/lb F[a]	0.21 – 0.23
$G - 10^6$ psi	3.8 – 4.1	K – Btu ft/hr ft^2 F[b]	71 – 96[d]
μ	0.32 – 0.33	$\alpha - 10^6$ in/in F[c]	12.3 – 13.3

(a) 212 F.
(b) 77 F.
(c) 77 – 212 F.
(d) Thermal conductivity can vary significantly with alloy type and processing conditions.

TABLE 22. CONDENSED DESIGN PROPERTY DATA FOR 2014 ALUMINUM

Structural Form (Source)		Extruded Shapes (1)			
Section or Wall Thickness, in.		0.125 - 1.75	1.75 - 4.50	0.125 - 4.50	
Thermal Treatment		T6, T6510, and T6511		T62	
Test Temperature, F		75	75	75	
		(A and B Values)	(S Values)	(S Values)	
Mechanical					
F_{tu}, ksi	L	60-71	68	60	
	LT	58-64			
	ST				
F_{ty}, ksi	L	53-63	60	53	
	LT	49-55			
	ST				
F_{cy}, ksi	L	52-62			
	LT	53-57			
	ST				
F_{su}, ksi	L	37-43			
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L	90-100			
	LT				
	ST				
(e/D=2.0)	L	115-128			
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L	73-80			
	LT				
	ST				
(e/D=2.0)	L	85-94			
	LT				
	ST				
e, percent in 2.0 in.	L	7		6-7	
	LT	2-5			
	ST				

TABLE 23. TYPICAL PROPERTY DATA FOR 2014 ALUMINUM

Structural Form (Source)		Extruded Shapes (6)	
Section or Wall Thickness, in.		0.30	
Thermal Treatment		T62	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	75	
	LT	72	
	ST		
F_{ty}, ksi	L	67	
	LT	67	
	ST		
F_{cy}, ksi	L	70	
	LT	71	
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	12	
	LT	5	
	ST		

TABLE 24. CONDENSED DESIGN PROPERTY DATA FOR 2024 ALUMINUM

Structural Form (Source)		Drawn Tubing (1)		Extruded Shapes (1)		
Section or Wall Thickness, in.		0.018-0.500		<0.25-4.50	All	0.05-4.50
Thermal Treatment		T3	T42	T4, T3510, T3511	T42	T81, T8510, T8511
Test Temperature, F		75		75		
		(A and B Values)	(S Values)	(A and B Values)	(S Values)	
Mechanical						
F_{tu}, ksi	L	64-66	64	57-74	57	64-66
	LT			54-60	50	61-64
	ST					
F_{ty}, ksi	L	42-45	40	42-54	38	56-58
	LT			37-43	36	55-57
	ST					
F_{cy}, ksi	L	42-45	40	34-50	38	57-59
	LT			40-47	38	57-59
	ST					
F_{su}, ksi	L	39-40	39	29-36	30	35-36
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L	96-99	96	78-93	85	92-96
	LT					
	ST					
(e/D=2.0)	L	122-126	122	97-118	108	117-123
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L	59-63	56	55-68	53	79-82
	LT					
	ST					
(e/D=2.0)	L	67-72	64	67-79	61	93-96
	LT					
	ST					
e, percent in 2.0 in.	L	10	10	10-12	8-12	4-5
	LT			2-6		
	ST					

TABLE 25. TYPICAL PROPERTY DATA FOR 2024 ALUMINUM

Structural Form (Source)		Extruded Shapes (6)			Extruded Shapes (4)
Section or Wall Thickness, in.		0.26-4.00	2.56		0.50-4.00
Thermal Treatment		T8511	T42	T62	T8510
Test Temperature, F		75			75
Mechanical					
F_{tu}, ksi	L	69-77	81	71	
	LT	65-77	66	54	
	ST				
F_{ty}, ksi	L	60-71	58	59	
	LT	60-73	45	53	
	ST				
F_{cy}, ksi	L	61-74	60	61	
	LT	63-73	49	56	
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 2.0 in.	L	10-12	15	12	
	LT	2-12	10	6	
	ST				

TABLE 26. CONDENSED DESIGN PROPERTY DATA FOR 2219 ALUMINUM

Structural Form (Source)		Extruded Shapes and Tubing (2)			
Section or Wall Thickness, in.		< 3.00			
Thermal Treatment		T31, T3510, T3511	T62	T81, T8510, T8511	
Test Temperature, F			75		
			(Minimum Values)		
Mechanical					
F_{tu}, ksi	L	42-45	54	58	
	LT				
	ST				
F_{ty}, ksi	L	26-27	36	42	
	LT				
	ST				
F_{cy}, ksi	L				
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 2.0 in.	L	14	6	6	
	LT				
	ST				

TABLE 27. TYPICAL PROPERTY DATA FOR 2219 ALUMINUM

Structural Form (Source)		Extruded Shapes (7)	
Section or Wall Thickness, in.		≤ 0.50-3.00	
Thermal Treatment		T8510, T8511	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	58	
	LT	56	
	ST		
F_{ty}, ksi	L	42	
	LT	39	
	ST		
F_{cy}, ksi	L	43	
	LT	41-43	
	ST		
F_{su}, ksi	L	33	
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L	81-87	
	LT		
	ST		
(e/D=2.0)	L	107-113	
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L	67-69	
	LT		
	ST		
(e/D=2.0)	L	82-84	
	LT		
	ST		
e, percent in 2.0 in.	L	6	
	LT	4	
	ST		

TABLE 28. TYPICAL PROPERTY DATA FOR X2618 ALUMINUM

Structural Form (Source)		Extruded Shapes (8)
Section or Wall Thickness, in.		2.00
Thermal Treatment		T6511
Test Temperature, F		75
Mechanical		
F_{tu}, ksi	L	63
	LT	61
	ST	
F_{ty}, ksi	L	57
	LT	55
	ST	
F_{cy}, ksi	L	
	LT	
	ST	
F_{su}, ksi	L	
	LT	
	ST	
F_{bru}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
F_{bry}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
e, percent in 2.0 in.	L	12
	LT	7
	ST	

TABLE 29. CONDENSED DESIGN PROPERTY DATA FOR 5083 ALUMINUM

Structural Form (Source)		Extruded Shapes (1)		
Section or Wall Thickness, in.		∠0.50		0.50-5.00
Thermal Treatment		0	H111	H111
Test Temperature, F		75		
		(S Values)		
Mechanical				
F_{tu}, ksi	L	39	40	40
	LT		40	32
	ST			
F_{ty}, ksi	L	16	24	24
	LT		24	19
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	14	12	12
	LT			
	ST			

TABLE 30. CONDENSED DESIGN PROPERTY DATA FOR 5086 ALUMINUM

Structural Form (Source)		Extruded Shapes (1)	
Section or Wall Thickness, in.		≤ 5.00	
Thermal Treatment		0	H111
Test Temperature, F		75	
		(S Values)	
Mechanical			
F_{tu}, ksi	L	35	36
	LT		
	ST		
F_{ty}, ksi	L	14	21
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	14	12
	LT		
	ST		

TABLE 31. CONDENSED DESIGN PROPERTY DATA FOR 5454 ALUMINUM

Structural Form (Source)		Extruded Shapes (1)		
Section or Wall Thickness, in.		≤ 5.00		
Thermal Treatment		0	H111	H112
Test Temperature, F		75		
		(S Values)		
Mechanical				
F_{tu}, ksi	L	31	33	31
	LT			
	ST			
F_{ty}, ksi	L	12	19	12
	LT			12
	ST			
F_{cy}, ksi	L	12		12
	LT			12
	ST			
F_{su}, ksi	L			19
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			43
	LT			
	ST			
(e/D=2.0)	L			56
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			20
	LT			
	ST			
(e/D=2.0)	L			40
	LT			
	ST			
e, percent in 2.0 in.	L	14	12	12
	LT			
	ST			

TABLE 32. CONDENSED DESIGN PROPERTY DATA FOR 5456 ALUMINUM

Structural Form (Source)	Extruded Shapes (1)			
Section or Wall Thickness, in.	≤ 5.00			
Thermal Treatment	O	H111	H112	
Test Temperature, F	75			
	(S Values)			
Mechanical				
F_{tu}, ksi - - - - - - - - - L	41	42	41	
LT				
ST				
F_{ty}, ksi - - - - - - - - - L	19	26	19	
LT				
ST				
F_{cy}, ksi - - - - - - - - - L	19		19	
LT			19	
ST				
F_{su}, ksi - - - - - - - - - L			23	
LT				
ST				
F_{bru}, ksi (e/D=1.5) - - - - L			57	
LT				
ST				
(e/D=2.0) - - - - L			74	
LT				
ST				
F_{bry}, ksi (e/D=1.5) - - - - L			34	
LT				
ST				
(e/D=2.0) - - - - L			38	
LT				
ST				
e, percent in 2.0 in. L	14	12	12	
LT				
ST				

TABLE 33. CONDENSED DESIGN PROPERTY DATA FOR 6061 ALUMINUM

Structural Form (Source)	Extruded Shapes (1)		Drawn Shapes (1)		Drawing Tubing (1)	
Section or Wall Thickness, in.	≤3.00	≤0.25-6.50	≤8.00		0.025-0.500	
Thermal Treatment	T4, T4510, T4511	T6, T6510, T6511	T4, T451	T6, T651	T4	T6
Test Temperature, F	75		75		75	
	(A and B Values)		(S Values)		(S Values)	
Mechanical						
F_{tu}, ksi - - - - - - - - - L	26	35-41	30	42	30	42
LT		33-40				
ST						
F_{ty}, ksi - - - - - - - - - L	16	35-38	16	35	16	35
LT		28-36				
ST						
F_{cy}, ksi - - - - - - - - - L	14	35-38	14	34	14	34
LT		30-38				
ST						
F_{su}, ksi - - - - - - - - - L	16	19-29	20	37	20	37
LT						
ST						
F_{bru}, ksi (e/D=1.5) - - - - L	42	49-69	48	67	48	67
LT						
ST						
(e/D=2.0) - - - - L	55	69-89	63	88	63	88
LT						
ST						
F_{bry}, ksi (e/D=1.5) - - - - L	22	42-58	22	49	22	49
LT						
ST						
(e/D=2.0) - - - - L	26	51-65	26	56	26	56
LT						
ST						
e, percent in 2.0 in. L	16	8-10	18	10	18	10
LT						
ST						

TABLE 34. TYPICAL PROPERTY DATA FOR 6061 ALUMINUM

Structural Form (Source)		Extruded Shapes (6)	
Section or Wall Thickness, in.		0.246	
Thermal Treatment		T62	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	48	
	LT	46	
	ST		
F_{ty}, ksi	L	44	
	LT	41	
	ST		
F_{cy}, ksi	L	45	
	LT	44	
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	17	
	LT	19	
	ST		

TABLE 35. TYPICAL PROPERTY DATA FOR 7005 ALUMINUM

Structural Form (Source)		Extruded Shapes (9)	Extruded Shapes (9)	
Section or Wall Thickness, in.		Not Given	Not Given	
Thermal Treatment		T53	T53	
Test Temperature, F		75	75	
Mechanical				
F_{tu}, ksi	L	57	60	
	LT	48		
	ST			
F_{ty}, ksi	L	50	53	
	LT	42		
	ST			
F_{cy}, ksi	L	43		
	LT	44		
	ST			
F_{su}, ksi	L	32		
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L	72		
	LT			
	ST			
(e/D=2.0)	L	95		
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L	59		
	LT			
	ST			
(e/D=2.0)	L	73		
	LT			
	ST			
e, percent in 2.0 in.	L	15	15	
	LT			
	ST			

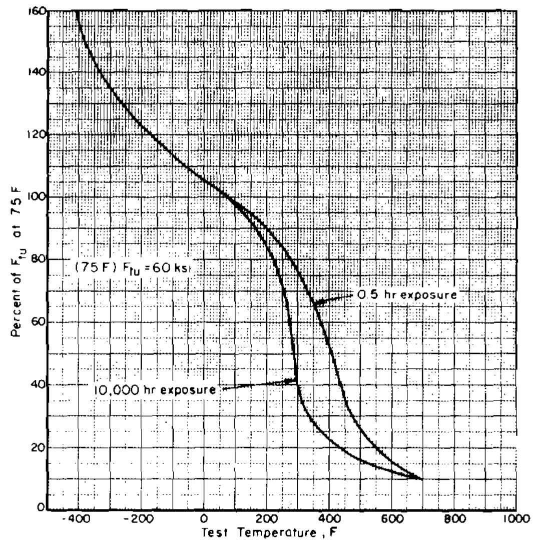


FIGURE 2. EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH OF 7005-T53 ALUMINUM

Source (6)

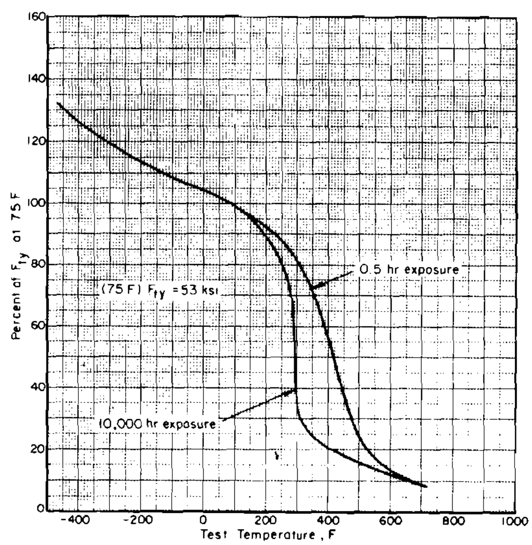


FIGURE 3. EFFECT OF TEMPERATURE ON TENSILE YIELD STRENGTH OF 7005-T53 ALUMINUM

Source (6)

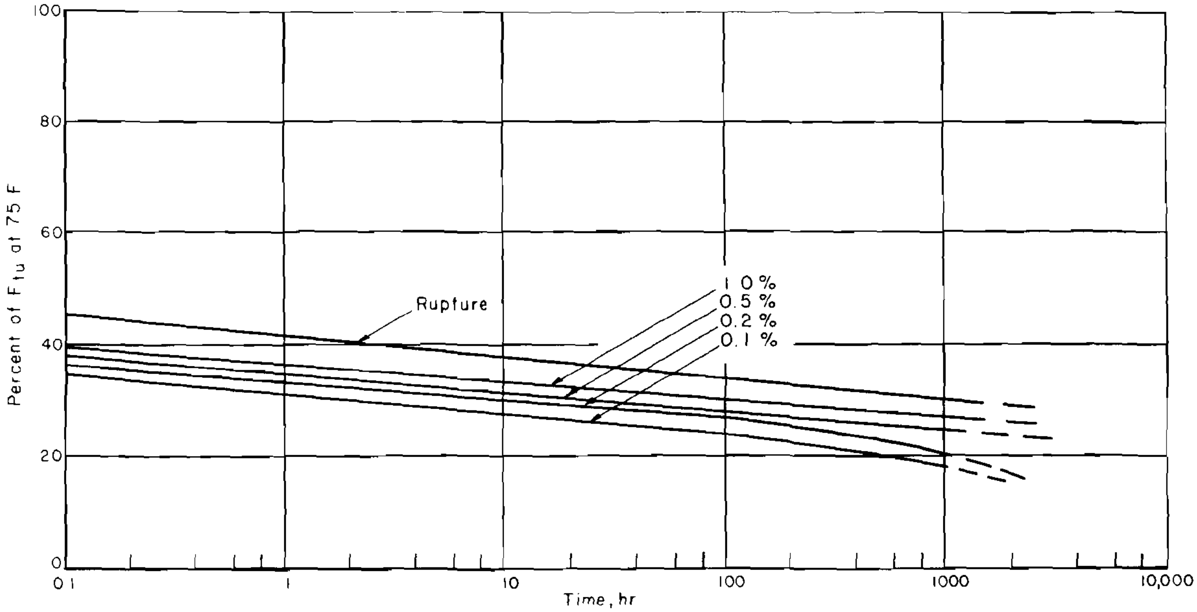


FIGURE 4. CREEP AND STRESS RUPTURE CURVES OF 7005-T53 ALUMINUM AT 212 F

Source (6)

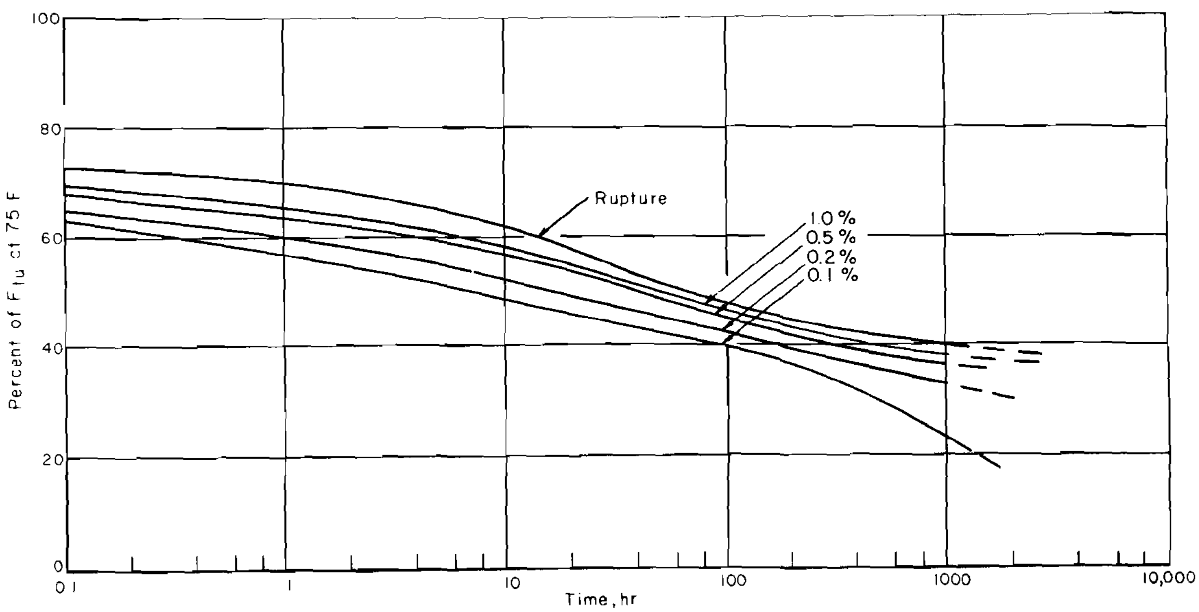


FIGURE 5. CREEP AND STRESS RUPTURE CURVES OF 7005-T53 ALUMINUM AT 300 F

Source (6)

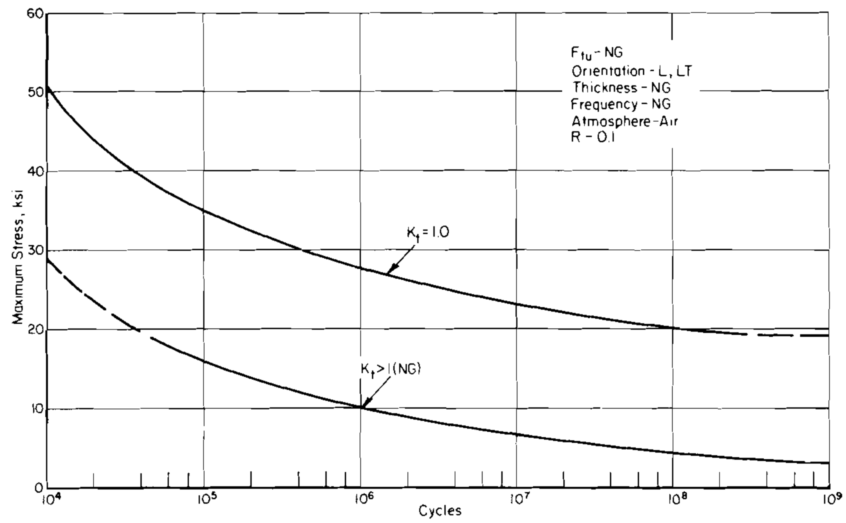


FIGURE 6. ROTATING-BEAM FATIGUE CURVES FOR 7005-T6, 7005-T53, AND 7005-T63 ALUMINUM AT 75 F

Source (6)

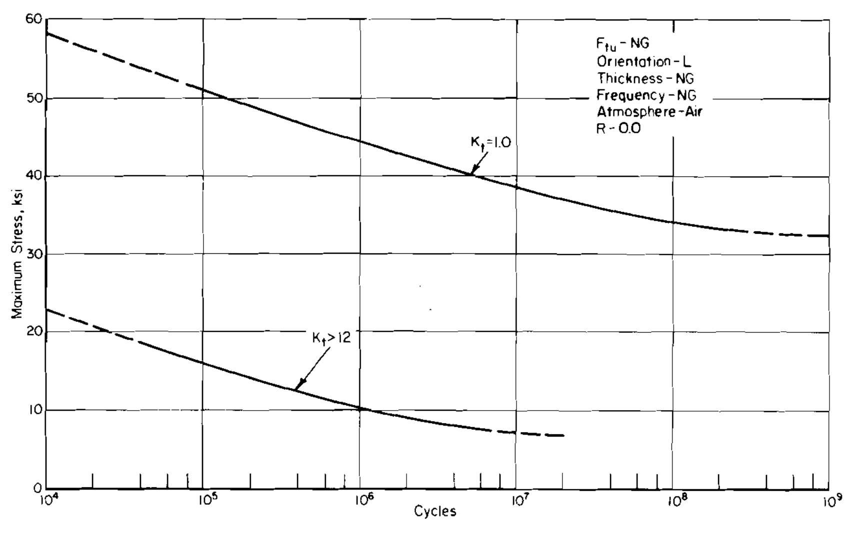


FIGURE 7. AXIAL FATIGUE CURVES FOR 7005-T53 ALUMINUM AT 75 F

Source (6)

TABLE 36. TYPICAL PROPERTY DATA FOR 7049 ALUMINUM

Structural Form (Source)		Extruded Shapes (10)			Extruded Bar (11)			
Section or Wall Thickness, in.		0.70	3.50		4.00			
Thermal Treatment		T73		T76	T76			
Test Temperature, F		75			75	250	350	500
Mechanical								
F_{tu}, ksi	L	82-83	80-82	82-83	81-87	64-65	48-49	17-19
	LT	82-83	76	77	76	58-59	44-46	16-17
	ST	76-77	74-75	75-76	76			
F_{ty}, ksi	L	74-77	72-75	75-76	72-81	63-64	48	17-19
	LT	74-75	67-68	69	67-68	56-57	43-45	16
	ST	68-69	64-67	64-69	67-68			
F_{cy}, ksi	L				75-81	66-72	50-54	19
	LT				73-76	63-64	49	18
	ST							
F_{su}, ksi	L				45-46			
	LT				42-45			
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 1.0 in.	L	12	11	11-12	12-13	22-23	24-29	35-40
	LT	12	11-12	11-12	11-12	16-18	19-22	29-37
	ST	4-5	6-9	7-11	11-12			

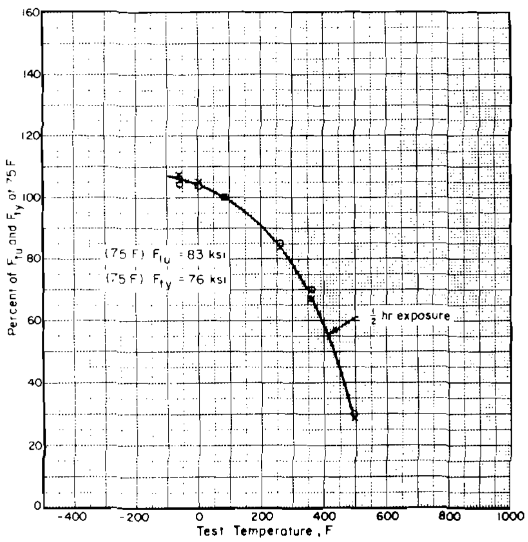


FIGURE 8. EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH AND TENSILE YIELD STRENGTH FOR 7049-T76 AND 7049-T73 ALUMINUM

Source (10)

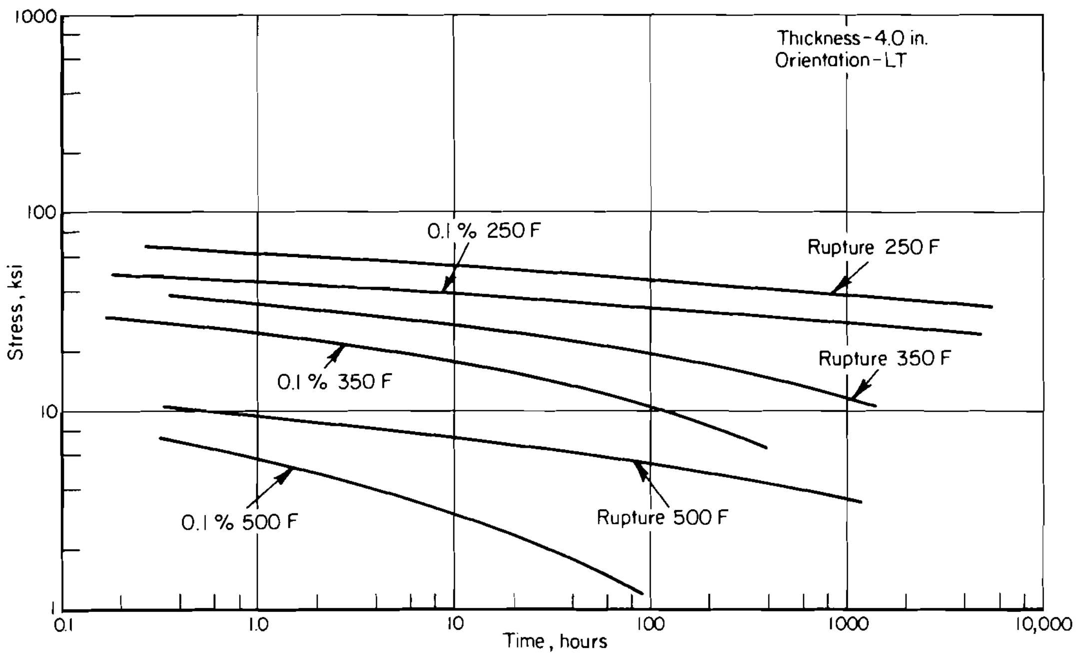


FIGURE 9. CREEP AND STRESS RUPTURE CURVES FOR 7049-T76 ALUMINUM AT ELEVATED TEMPERATURES

Source (11)

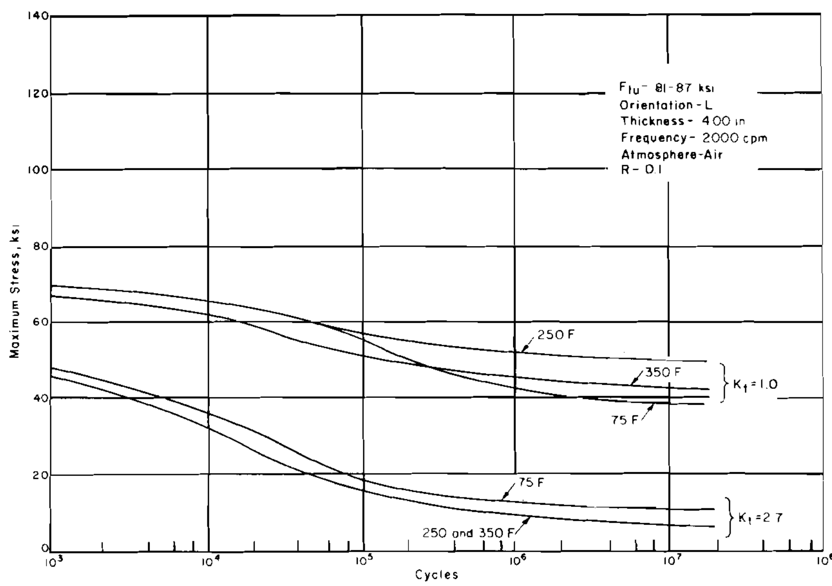


FIGURE 10. AXIAL FATIGUE CURVES FOR 7049-T46 ALUMINUM AT ELEVATED TEMPERATURES

Source (11)

TABLE 37. TYPICAL PROPERTY DATA FOR 7050 ALUMINUM

Structural Form (Source)	Extruded Shapes (12)		Extruded Shapes (12)
Section or Wall Thickness, in.	≤4.50	≤3.00	0.187-5.00
Thermal Treatment	T736511	T76511	T7651X
Test Temperature, F	75		75
	(Tentative Minimum Values)		
Mechanical			
F_{tu}, ksi L	75-59	78-81	82-88
LT			76-85
ST			76-82
F_{ty}, ksi L	67-70	70-73	76-82
LT			71-77
ST			67-71
F_{cy}, ksi L			77-85
LT			75-81
ST			75-82
F_{su}, ksi L			46-50
LT			44-50
ST			39-44
F_{bru}, ksi (e/D=1.5) L			119-128
LT			106-131
ST			
(e/D=2.0) L			156-164
LT			143-168
ST			
F_{bry}, ksi (e/D=1.5) L			101-110
LT			101-113
ST			
(e/D=2.0) L			116-124
LT			115-136
ST			
e, percent in 2.0 in. L	7	7	10-14
LT			3-13
ST			3-13

TABLE 38. CONDENSED DESIGN PROPERTY DATA FOR 7075 ALUMINUM

Structural Form (Source)	Drawn Shapes (1)	Extruded Shapes (1)	Extruded Shapes (1)	Extruded Shapes (1)
Section or Wall Thickness, in.	≤1.00-4.00	≤0.25-5.00	≤0.062-4.50	≤0.125-1.00
Thermal Treatment	T6, T651	T6, T6510, T6511	T73, T73510, T73511	T76, T76510, T6511
Test Temperature, F	75	75	75	75
	(A and B Values)	(A and B Values)	(S Values)	(S Values)
Mechanical				
F_{tu}, ksi L	77-79	78-85	65-70	74-75
LT	69-79	65-81	57-67	70-72
ST				
F_{ty}, ksi L	66-68	68-77	55-61	64-65
LT	60-68	50-70	46-58	59-61
ST				
F_{cy}, ksi L	64-66	68-77	55-61	64-65
LT		56-78	49-62	64-66
ST				
F_{su}, ksi L	46-47	37-45	35-38	39-40
LT				
ST				
F_{bru}, ksi (e/D=1.5) L	100-103	100-122	92-104	107-110
LT				
ST				
(e/D=2.0) L	123-126	135-153	121-134	136-139
LT				
ST				
F_{bry}, ksi (e/D=1.5) L	86-88	83-101	71-85	86-89
LT				
ST				
(e/D=2.0) L	92-95	99-121	83-102	102-105
LT				
ST				
e, percent in 2.0 in. L	7	6-8	7-8	7
LT	1-4	1-5		
ST				

TABLE 39. TYPICAL PROPERTY DATA FOR 7075 ALUMINUM

Structural Form (Source)		Extruded Shapes (6)			Extruded Shapes (14)
Section or Wall Thickness, in.		1.225	0.21-5.00		0.125-2.00
Thermal Treatment		T62	T73	T73510	T76, T76510, T76511
Test Temperature, F		75			75
Mechanical					
F_{tu}, ksi	L	84	75	73-77	75-85
	LT	80	72	65-76	76-79
	ST				
F_{ty}, ksi	L	75	67	65-69	64-78
	LT	71	64	54-68	64-73
	ST				
F_{cy}, ksi	L	80	72	66-71	98-103
	LT	77	70	58-71	97-109
	ST				
F_{su}, ksi	L				53-59
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				114-154
	LT				
	ST				
(e/D=2.0)	L				176-197
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				119-139
	LT				
	ST				
(e/D=2.0)	L				134-162
	LT				
	ST				
e, percent in 2.0 in.	L	14	12		9-12
	LT	8	8		10-12
	ST				

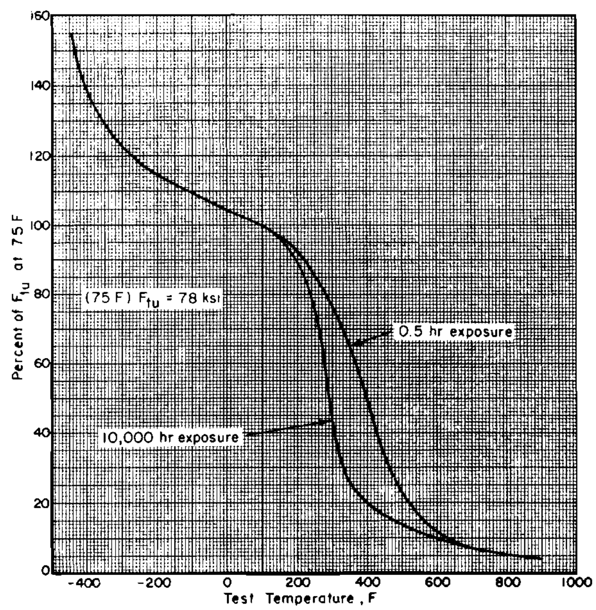


FIGURE 11. EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH OF 7075-T76 AND -T7651 ALUMINUM

Source (13)

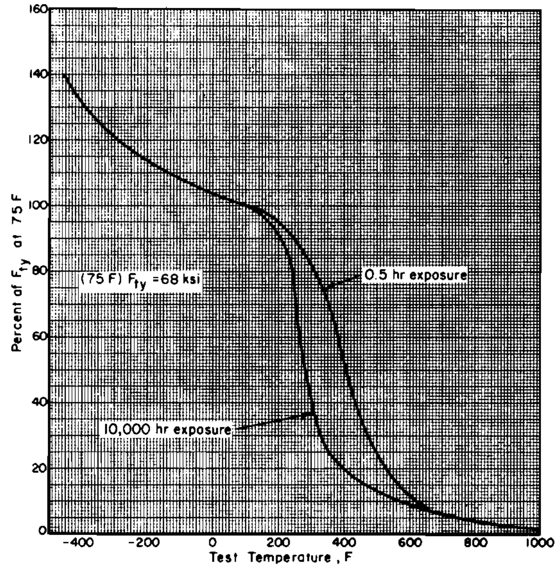


FIGURE 12. EFFECT OF TEMPERATURE ON TENSILE YIELD STRENGTH OF 7075-T76 AND -T7651 ALUMINUM

Source (13)

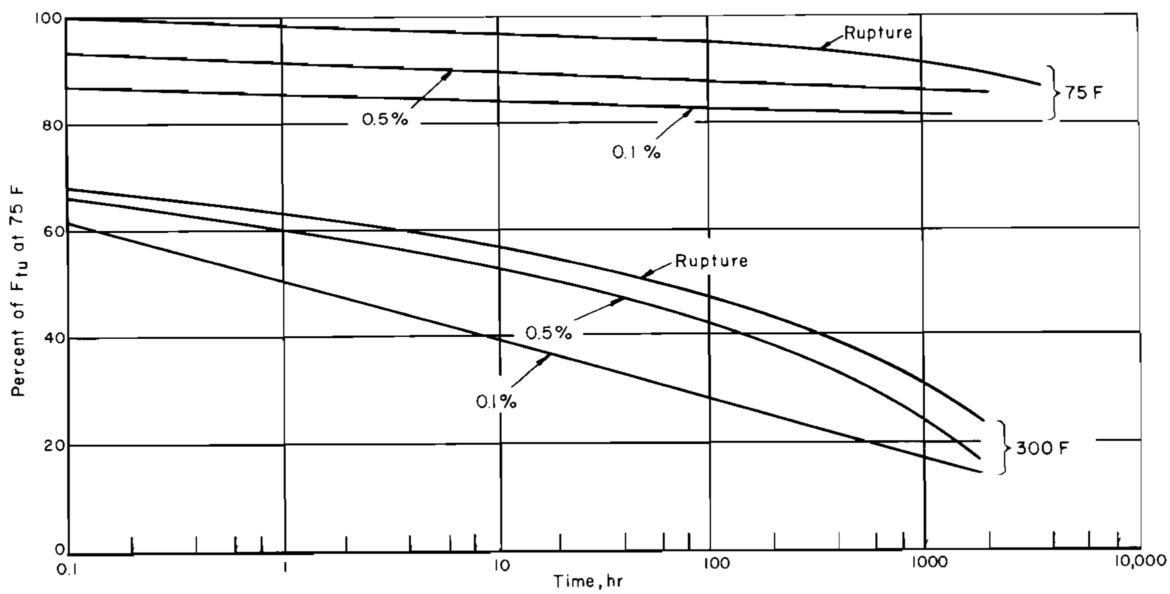


FIGURE 13. CREEP AND STRESS RUPTURE CURVES FOR 7075-T76 AND -T7651 ALUMINUM

Source (13)

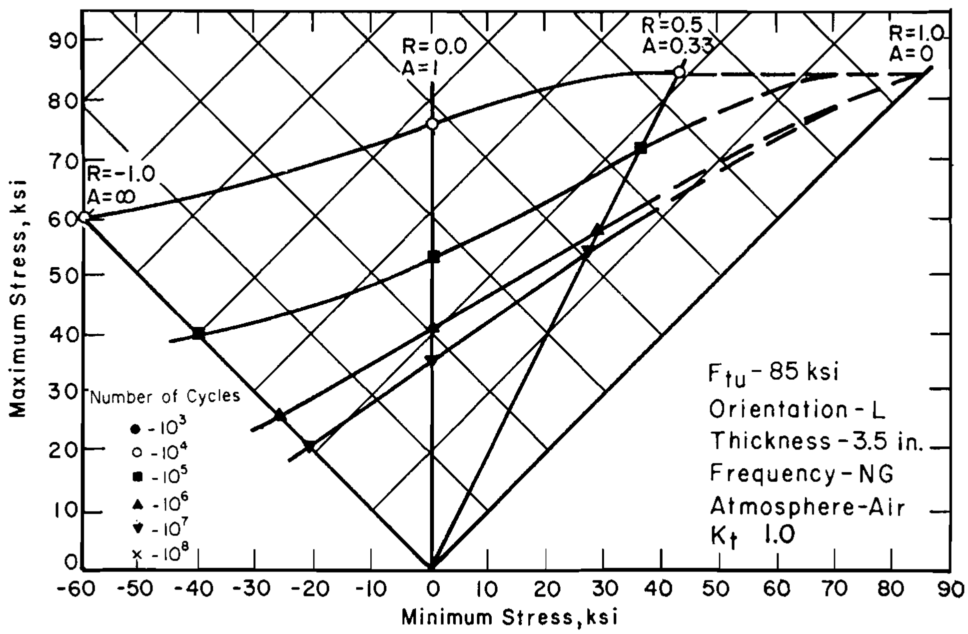


FIGURE 14. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

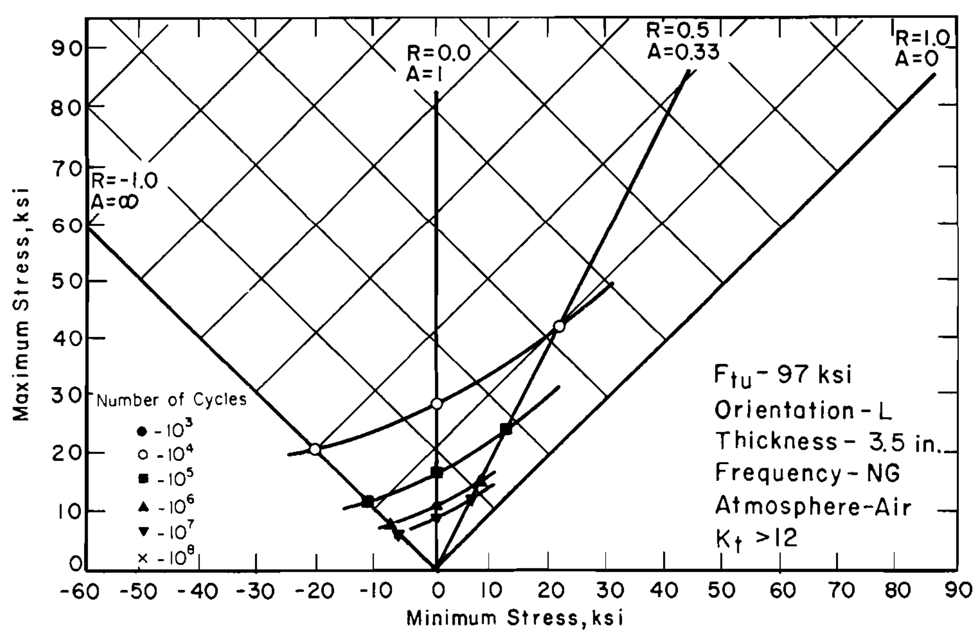


FIGURE 15. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

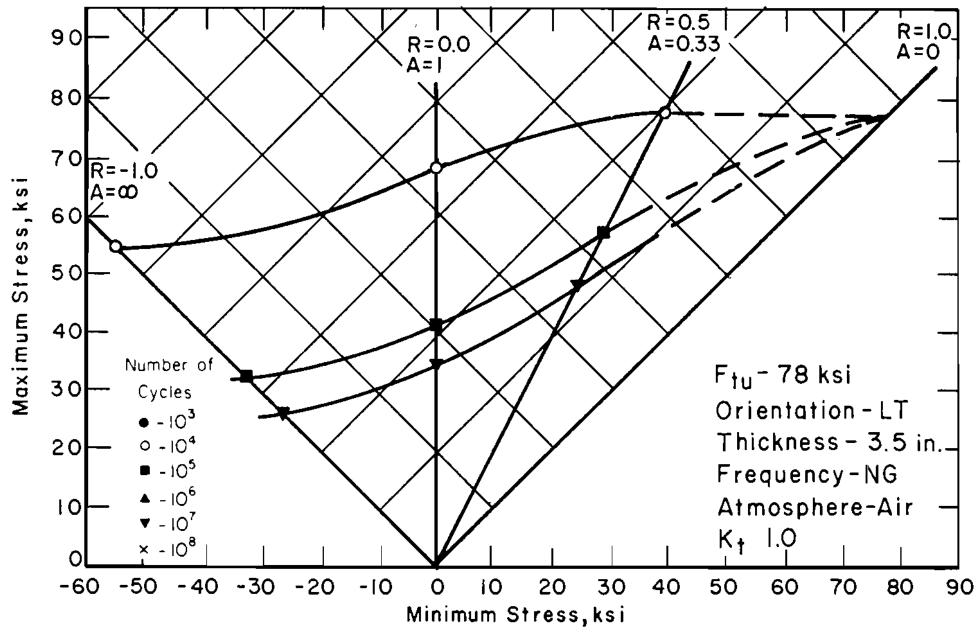


FIGURE 16. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

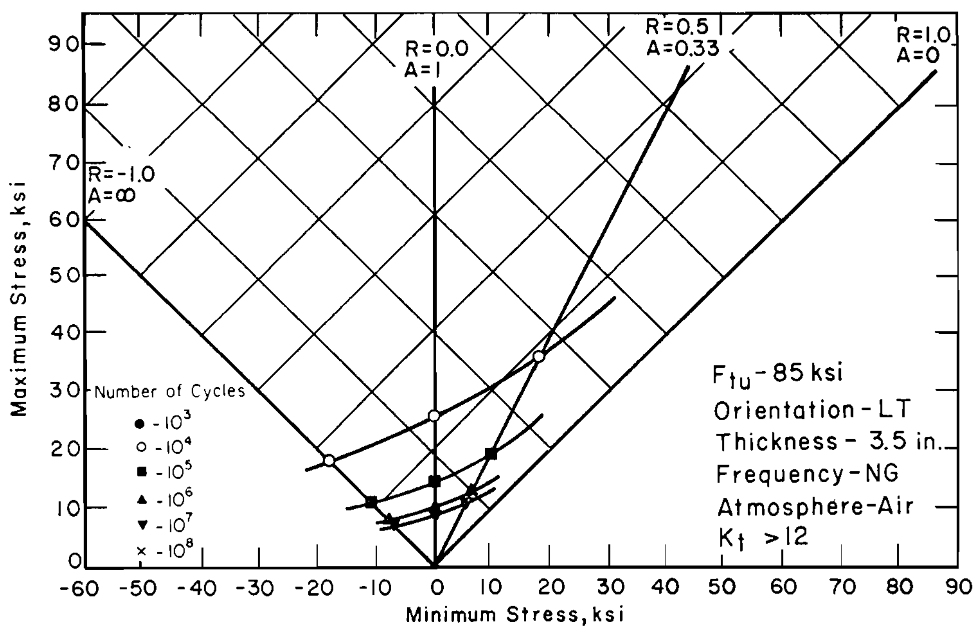


FIGURE 17. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

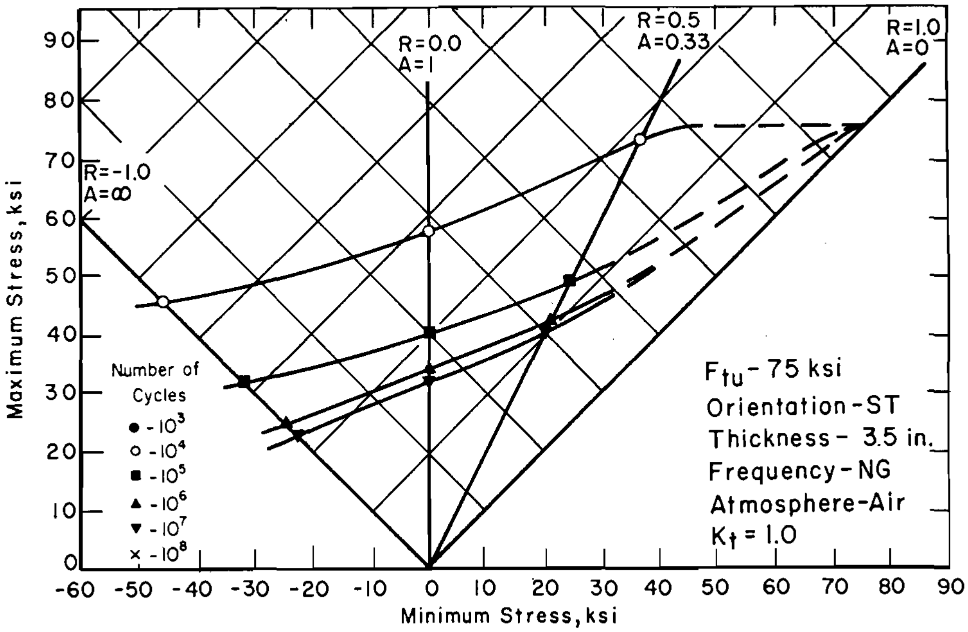


FIGURE 18. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

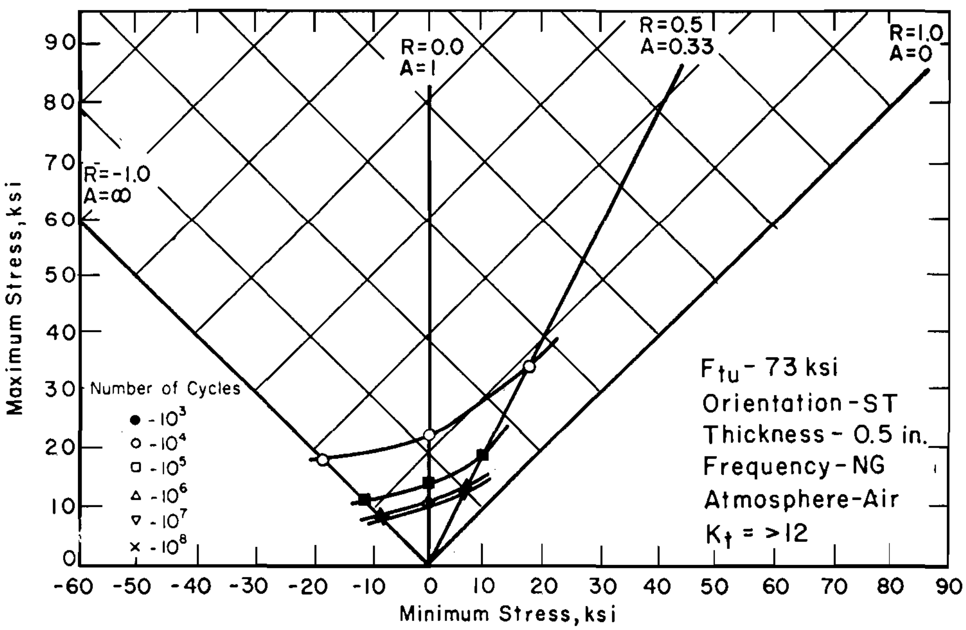


FIGURE 19. AXIAL FATIGUE DATA FOR 7075-T6510 ALUMINUM AT 75 F

Source (4)

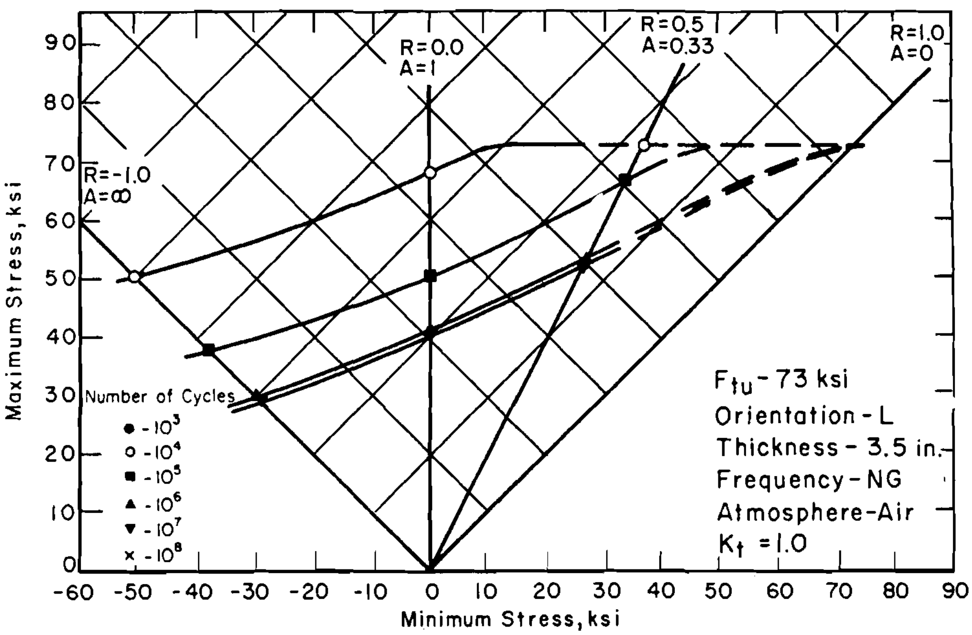


FIGURE 20. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

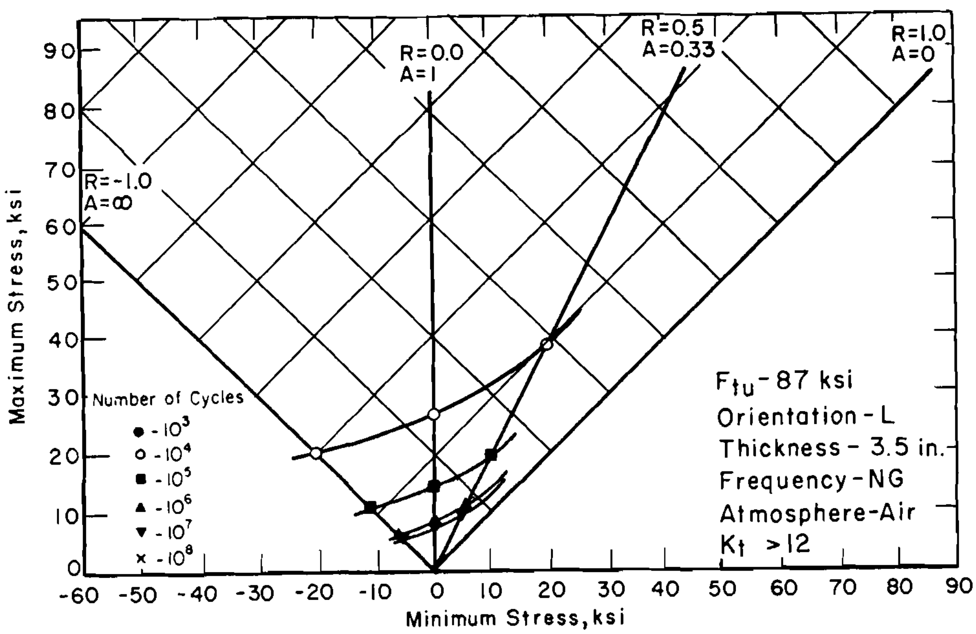


FIGURE 21. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

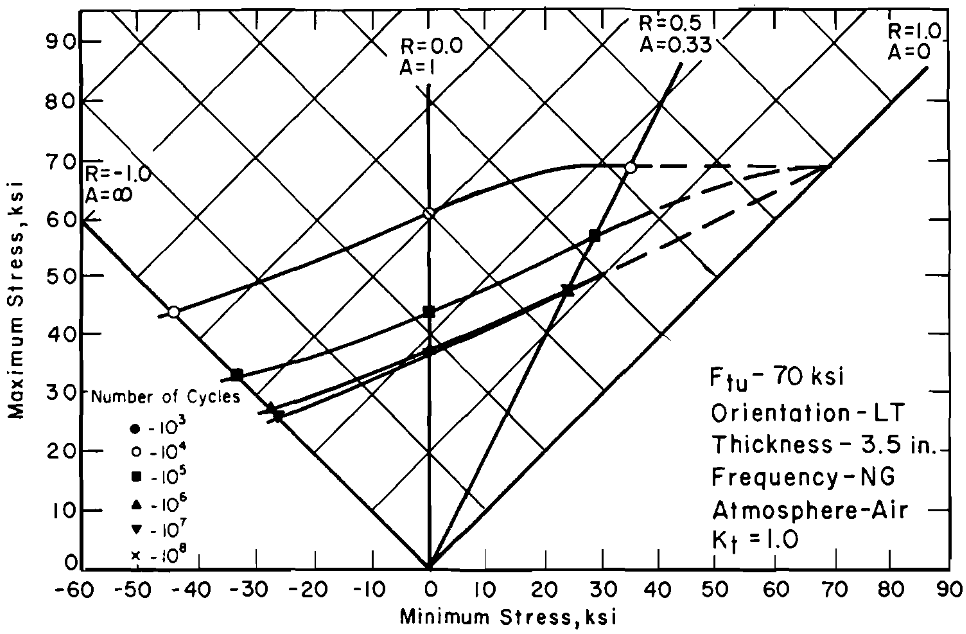


FIGURE 22. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

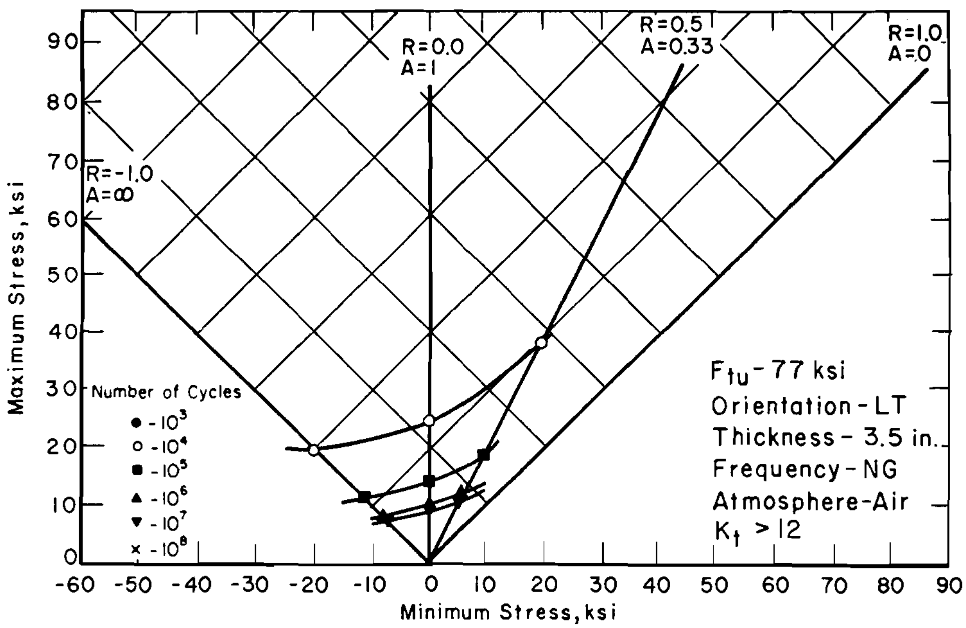


FIGURE 23. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

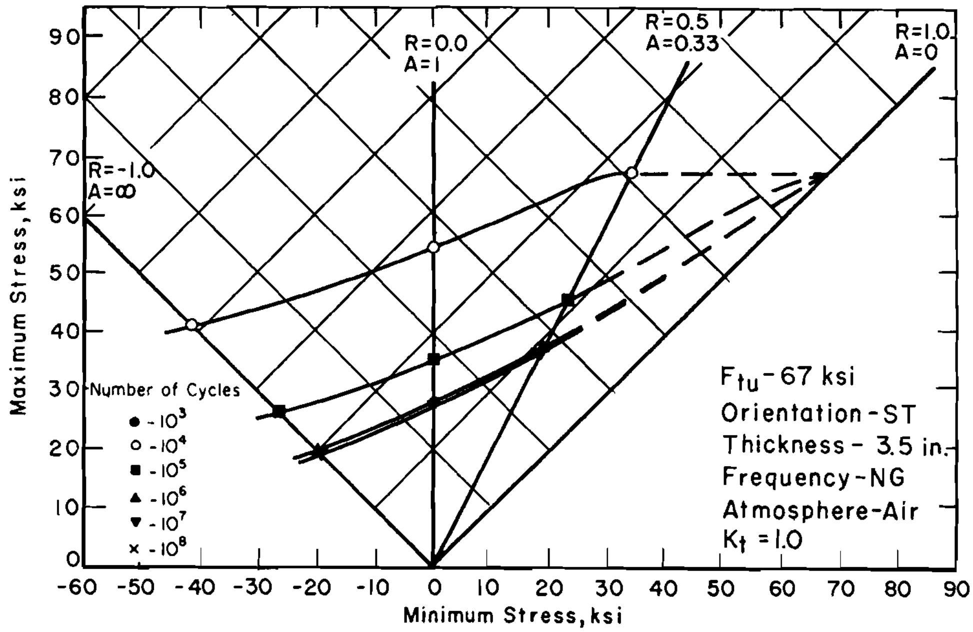


FIGURE 24. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

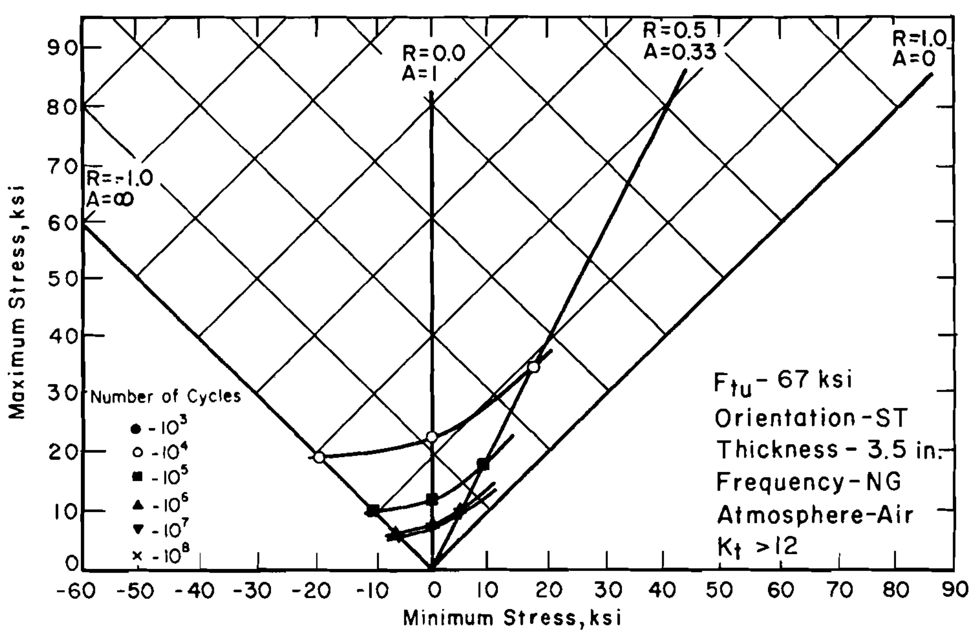


FIGURE 25. AXIAL FATIGUE DATA FOR 7075-T73510 ALUMINUM AT 75 F

Source (4)

TABLE 40. CONDENSED DESIGN PROPERTY DATA FOR 7079 ALUMINUM

Structural Form (Source)		Extruded Shapes (1)	
Section or Wall Thickness, in.		≤0.25-7.00	
Thermal Treatment		T6, T6510, T6511	
Test Temperature, F		75	
		(S Values)	
Mechanical			
F_{tu}, ksi	L	75-79	
	LT	63-70	
	ST		
F_{ty}, ksi	L	64-70	
	LT	52-62	
	ST		
F_{cy}, ksi	L	64-71	
	LT	56-57	
	ST		
F_{su}, ksi	L	41-43	
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L	89-112	
	LT		
	ST		
(e/D=2.0)	L	118-140	
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L	70-90	
	LT		
	ST		
(e/D=2.0)	L	90-103	
	LT		
	ST		
e, percent in 2.0 in.	L	4-7	
	LT	2-6	
	ST		

TABLE 41. TYPICAL PROPERTY DATA FOR 7079 ALUMINUM

Structural Form (Source)		Extruded Shapes (5)		
Section or Wall Thickness, in.		0.222	0.146-0.50	
Thermal Treatment		T62	T6511	
Test Temperature, F		75		
Mechanical				
F_{tu}, ksi	L	84	82-85	
	LT		79-81	
	ST			
F_{ty}, ksi	L	76	74-78	
	LT		71-73	
	ST			
F_{cy}, ksi	L	80	74-77	
	LT		77-78	
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	12	11-16	
	LT		4	
	ST			

TABLE 42. CONDENSED DESIGN PROPERTY DATA FOR 7178 ALUMINUM

Structural Form (Source)	Extruded Shapes (1)			
Section or Wall Thickness, in.	≤0.061-1.50	1.50-3.00	≤0.061-3.00	≤0.125-1.00
Thermal Treatment	T6, T6510, T6511		T62	T76, T76510, T76511
Test Temperature, F	75			
	(A and B Values)	(S Values)	(S Values)	(S Values)
Mechanical				
F_{tu}, ksi — L	82-90	82-86	79-86	76-77
LT	79-85			71-74
ST				
F_{ty}, ksi — L	76-81	71-77	71-77	66-67
LT	69-75			61-63
ST				
F_{cy}, ksi — L	75-80			67-68
LT	76-82			67-69
ST				
F_{su}, ksi — L	42-46			42-43
LT				
ST				
F_{bru}, ksi (e/D=1.5) — L	107-128			112-114
LT				
ST				
(e/D=2.0) — L	131-160			139-141
LT				
ST				
F_{bry}, ksi (e/D=1.5) — L	99-106			90-92
LT				
ST				
(e/D=2.0) — L	106-123			106-107
LT				
ST				
e, percent in 2.0 in. — L	5	5	5	7
LT				
ST				

TABLE 43. TYPICAL PROPERTY DATA FOR 7178 ALUMINUM

Structural Form (Source)	Extruded Shapes (5,6)	
Section or Wall Thickness, in.	0.403	0.18-2.18
Thermal Treatment	T62	T6510
Test Temperature, F	75	
Mechanical		
F_{tu}, ksi — L	97	92-95
LT	92	82-92
ST		
F_{ty}, ksi — L	88	83-88
LT	83	74-86
ST		
F_{cy}, ksi — L	95	82-87
LT	94	80-95
ST		
F_{su}, ksi — L		
LT		
ST		
F_{bru}, ksi (e/D=1.5) — L		
LT		
ST		
(e/D=2.0) — L		
LT		
ST		
F_{bry}, ksi (e/D=1.5) — L		
LT		
ST		
(e/D=2.0) — L		
LT		
ST		
e, percent in 2.0 in. — L	11	9-12
LT	8	6-12
ST		

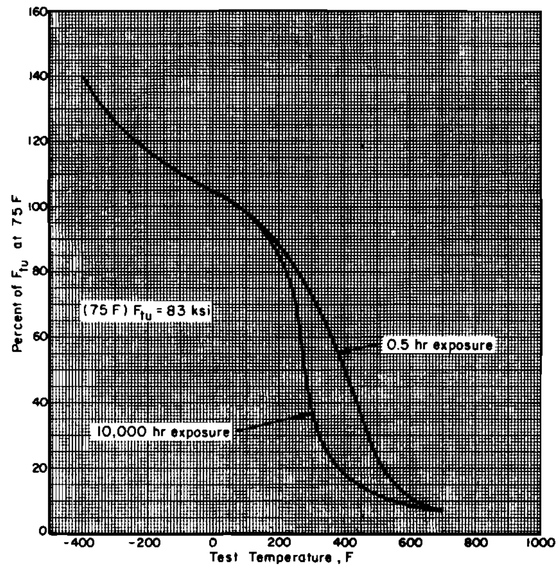


FIGURE 26. EFFECT OF TEMPERATURE ON ULTIMATE TENSILE STRENGTH OF 7178-T76 AND -T7651 ALUMINUM

Source (13)

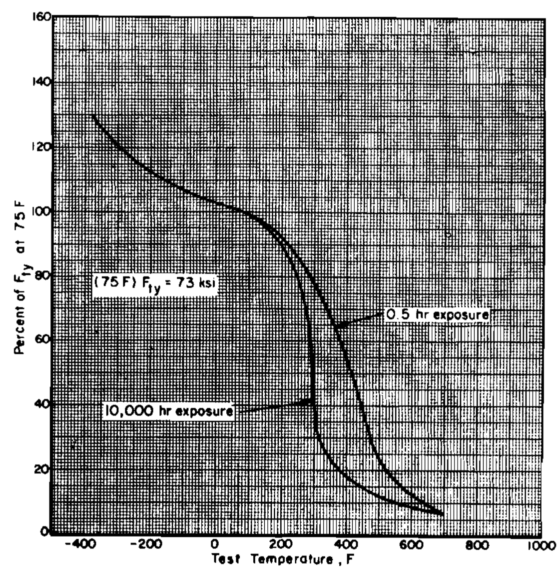


FIGURE 27. EFFECT OF TEMPERATURE ON TENSILE YIELD STRENGTH OF 7178-T76 AND -T7651 ALUMINUM

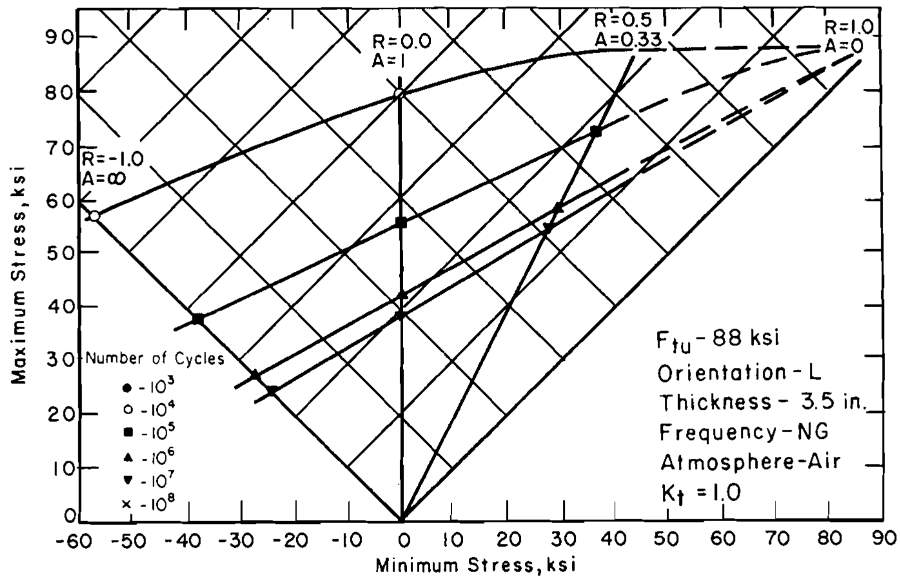


FIGURE 28. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

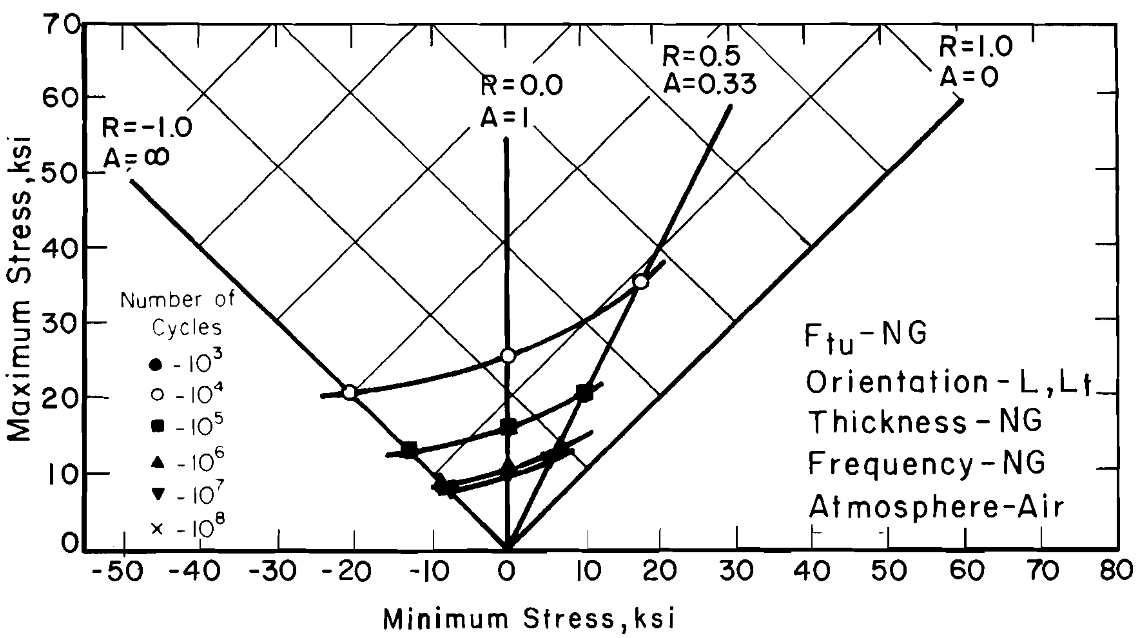


FIGURE 29. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

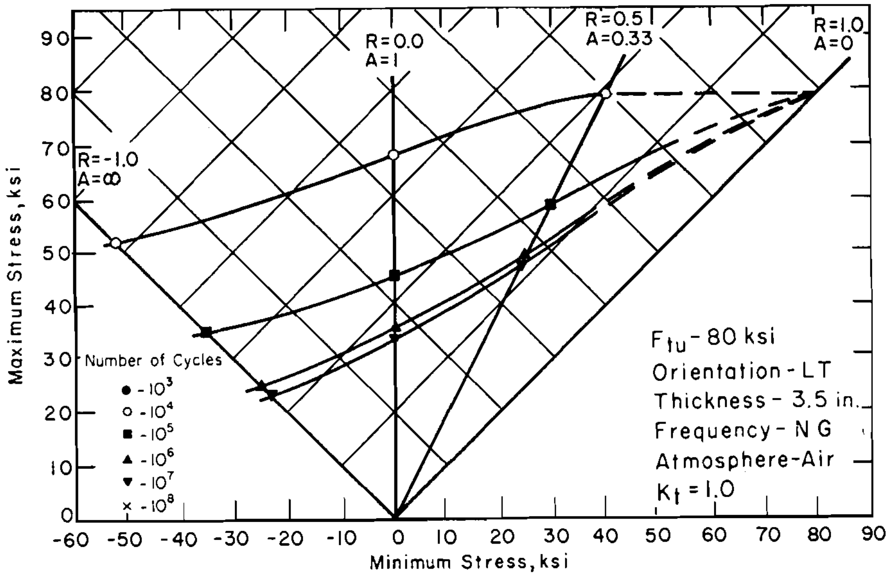


FIGURE 30. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

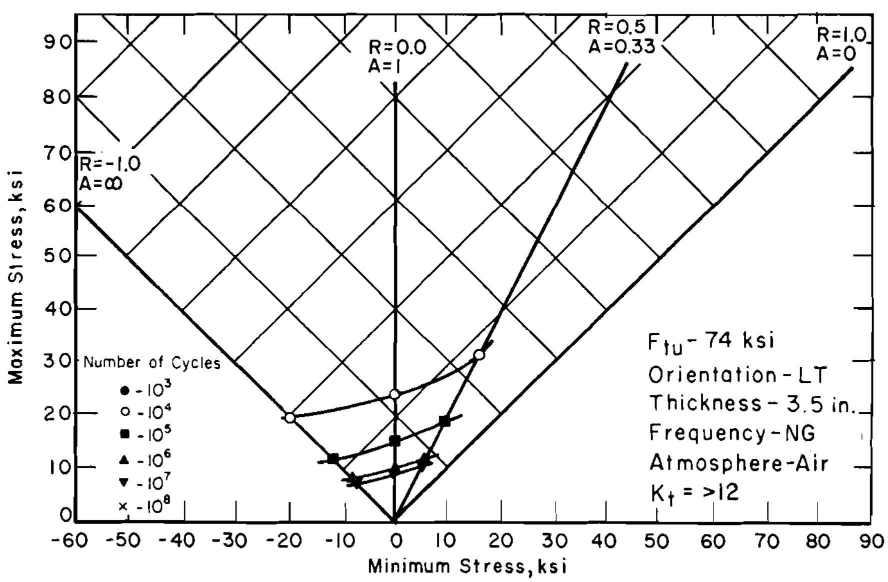


FIGURE 31. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

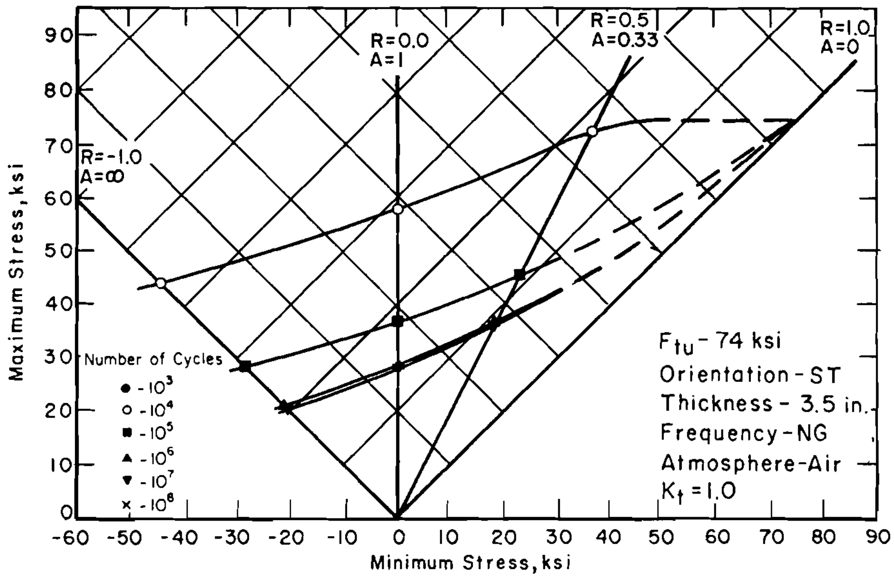


FIGURE 32. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

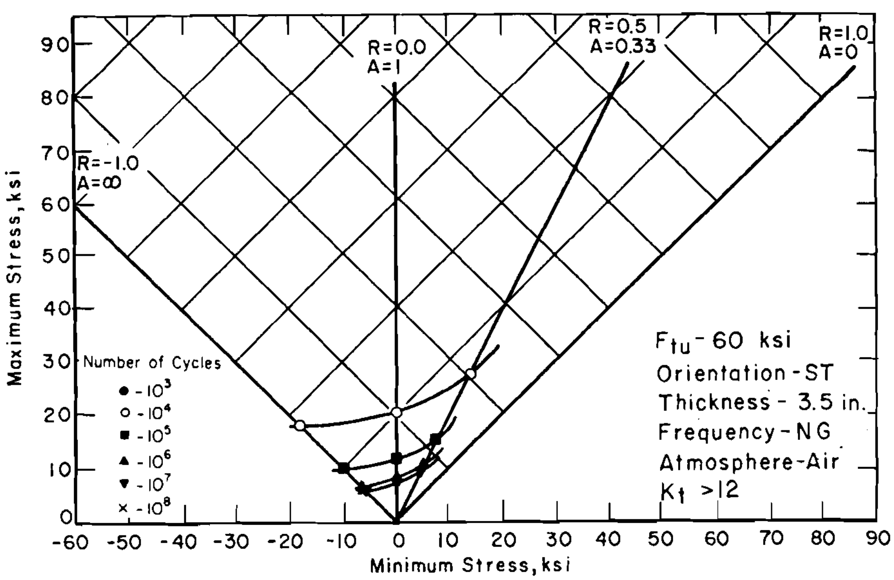


FIGURE 33. AXIAL FATIGUE DATA FOR 7178-T6510 ALUMINUM AT 75 F

Source (4)

TITANIUM

TITANIUM DATA SOURCES

(1) "Metallic Materials and Elements for Aerospace Vehicle Structures", Military Standardization Handbook (MIL-HDBK-5B), September, 1971.

(2) "Titanium Alloy Handbook" (MCIC-HB-02), Metals and Ceramics Information Center, Battelle's Columbus Laboratories, Columbus, Ohio, December 1972.

(3) Superior Tube Company Trade Literature (no date given).

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(5) Sevarens, E. W., "Evaluation of the Ti-3Al-2.5V Alloy", Ai-Research Document No. 67-2009, March, 1966.

(6) Mallory-Sharon Metals Corp., Technical Data Sheet for Ti-3Al-2.5V Alloy.

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(8) Olexa, J. M. et al., "The Manufacture of Aircraft Quality Hydraulic Tubing With the Ti-3Al-8V-6Cr-4Mo-4Zr Alloy", AFML-TR-71-111, April, 1971.

(9) "Facts About RMI Ti-3Al-8V-6Cr-4Mo-4Zr", RMI Company, Niles, Ohio 44446, August, 1972.

(10) Christiana, J. J., "Improved Methods for the Production of Titanium Alloy Extrusions", ATD-TR-63-7-556, December, 1963.

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(12) Brockett, R. M. and Gottbrath, "Development of Engineering Data on Titanium Extrusions for Use in Aerospace Design". AFML-TR-67-189, July, 1967.

(13) Gorecki, T. A., "Production Techniques for Extruding, Drawing and Heat Treatment of Titanium Alloys", AFML-TR-68-349.

(14) "Damage Tolerant Design Handbook", MCIC-HB-01, Metals and Ceramics Information Center, Battelle's Columbus Laboratories, Columbus, Ohio, December 1972.

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(16) "Titanium Alloy 6Al-4V Extrusions", FAA-55-72-02, March 1972.

(17) "Engineering Data on New and Emerging Structural Materials", AFML-TR-70-252, October, 1970.

(18) "Mechanical and Metallurgical Characteristics of Titanium Alloy 6Al-4V", FAA-55-72-13, July 1972.

(19) "Improved Production Method for Thin-Walled Titanium Tubing", AFML-TR-69-310, April, 1970.

(20) "Apollo Semi-Annual Materials Report", N.A.A., Inc., July, 1963.

(21) "Unpublished Test Data for Ti-6Al-4V and AM350 Tubing", SST Program Lockheed Aircraft Corp., June, 1972.

(22) Amateau, M. F. and Kendall, E. G., "A Review of Ti-6Al-6V-2 Sn Fatigue Behavior", Air Force Report SAMSO-TR-70-275, July 15, 1970.

(23) "Material Technology", Summary Report No. 1, January – June, 1965, The Boeing Company.

(24) Data from Lockheed Aircraft Corp. (no date given).

(25) Manufacturing Methods for Form Rolling Complex Shapes of High Strength Titanium Alloys, AFML-TR-69-220, August, 1969.

(26) Peterson, V. C., et al., "Manufacturing Procedures for a New High Strength Beta Titanium Alloy Having Superior Formability", AFML-TR-69-171, June, 1969.

TABLE 44. SUMMARY OF ROOM TEMPERATURE PHYSICAL AND ELASTIC PROPERTY DATA FOR TITANIUM ALLOYS (SOURCES 1,2)

Property	Unalloyed Titanium	Ti-3Al-2.5V	Ti-3Al-8V-6Cr-4Mo-4Zr	Ti-4Al-3Mo-1V	Ti-5Al-2.5Sn
Elastic					
E_t – 10^6 psi	15.5	14.1	14.0 - 15.4	15.5	15.5
E_c – 10^6 psi	16.0		14.8	16.0	15.5
G – 10^6 psi	6.0 - 6.5		5.8	6.0	5.9
μ –	0.32	0.31	0.33	0.32	0.32
Physical					
ω – lb/in.^{3}	0.163	0.162		0.162	0.162
C – Btu/lb-F[a]	0.12 - 0.13			0.12 - 0.13	0.13 - 0.14
K – Btu-ft/hr/ft^2-F[b]	10.0 - 11.5	4.4		4.0	4.3 - 4.5
α – 10^{-6} in./in.-F[c]	4.7 - 5.4		5.4[d]	5.0	5.2

Property	Ti-6Al-4V	Ti-6Al-6V-2Sn	Ti-7Al-4Mo	Ti-8Al-1Mo-1V	Ti-11.5Mo-6Zr-4.5Sn	Ti-13V-11Cr-3Al
Elastic						
E_t – 10^6 psi	16.0	16.5 - 17.0	16.2 - 16.9	17.5	10.0 - 15.0	14.5 - 15.5
E_c – 10^6 psi	16.4	16.5 - 17.5	16.2 - 16.9	18.0	11.0 - 16.0	15.5 - 16.5
G – 10^6 psi	6.1 - 6.2	5.7 - 6.5	6.1 - 6.4	6.7	3.9 - 5.9	5.7 - 6.1
μ –	0.32	0.32	0.32	0.32	0.33 - 0.36	0.32
Physical						
ω – lb/in.^{3}	0.160	0.164	0.162	0.158	0.183	0.174
C – Btu/lb-F[a]	0.13 - 0.14	0.15 - 0.17	0.12 - 0.13	0.12		0.12 - 0.13
K – Btu-ft/hr/ft^2-F[b]	4.2 - 4.8	4.2 - 5.0	3.7	3.5 - 4.2		4.2 - 5.0
α – 10^{-6} in./in.F[c]	5.3	5.0	5.6[a]	4.7	4.2	5.4

(a) 212 F.
(b) 75 F.
(c) 75 - 212 F.
(d) 75 - 900 F.
(e) 75 - 1000 F.

TABLE 45. CONDENSED DESIGN PROPERTY DATA FOR COMMERCIALLY PURE TITANIUM

Structural Form (Source)		Extruded Shapes (1)	
Section or Wall Thickness, in.		≤3.00	
Thermal Treatment		1000-1300F/30 min/AC	
Test Temperature, F		75	
		(S Values)	
Mechanical			
F_{tu}, ksi	L	40-80	
	LT		
	ST		
F_{ty}, ksi	L	30-70	
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	10-25	
	LT		
	ST		

TABLE 46. TYPICAL PROPERTY DATA FOR COMMERCIALLY PURE TITANIUM

Structural Form (Source)		Drawn Tubing (3)				
Section or Wall Thickness, in.		0.015				
Thermal Treatment		No. 1 Temper	Quarter Hard	No. 2 Temper	No. 3 Temper	
Test Temperature, F		75				
Mechanical						
F_{tu}, ksi	L	80	80	75-95	90-115	
	LT					
	ST					
F_{ty}, ksi	L	60-75	65-75	50-75	75-95	
	LT					
	ST					
F_{cy}, ksi	L					
	LT					
	ST					
F_{su}, ksi	L					
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
e, percent in 2.0 in.	L	20	10	7-20	5-15	
	LT					
	ST					

TABLE 47. CONDENSED DESIGN PROPERTY DATA FOR Ti-3Al-2.5V

Structural Form (Source)		Drawn Tubing (2)
Section or Wall Thickness, in.		Not Given
Thermal Treatment		1375 F/15 min/AC
Test Temperature, F		75
		(S Values)
Mechanical		
F_{tu}, ksi	L	90
	LT	
	ST	
F_{ty}, ksi	L	75
	LT	
	ST	
F_{cy}, ksi	L	
	LT	
	ST	
F_{su}, ksi	L	
	LT	
	ST	
F_{bru}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
F_{bry}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
e, percent in 2.0 in.	L	15
	LT	
	ST	

TABLE 48. TYPICAL PROPERTY DATA FOR Ti-3Al-2.5V

Structural Form (Source)		Extruded and Drawn Tubing (4)	Extruded and Drawn Tubing (5)			
Section or Wall Thickness, in.		0.018-0.188	0.05			
Thermal Treatment		600 F/30 min/AC	1200 F/1 hr/AC			
Test Temperature, F		75	-452	-423	-32	75
Mechanical						
F_{tu}, ksi	L	116-152	195-205	218-221	171-172	101-103
	LT					
	ST					
F_{ty}, ksi	L	92-136	189-203	199-205	141-146	78-83
	LT					
	ST					
F_{cy}, ksi	L					
	LT					
	ST					
F_{su}, ksi	L					
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
e, percent in 1.0 in.	L	10-24	3-5		2-3	18-20
	LT					
	ST					

TABLE 49. TYPICAL PROPERTY DATA FOR Ti-3Al-2.5V

Structural Form (Source)		Extruded and Drawn Tubing (6)					
Section or Wall Thickness, in.		0.029					
Thermal Treatment		1650 F/20 min/WQ	1600 F/20 min/WQ plus 900 F/2 hrs/VC	1700 F/1 hr/WQ plus 900 F/6 hrs/VC			
Test Temperature, F		75			600	800	1000
Mechanical							
F_{tu}, ksi	L	103	129	132	96	89	59
	LT						
	ST						
F_{ty}, ksi	L	77	111	120	74	63	46
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 2.0 in.	L	20	7	11	8	11	36
	LT						
	ST						

TABLE 50. TYPICAL PROPERTY DATA FOR Ti-3Al-2.5V

Structural Form (Source)		Drawn Tubing (7)							
Section or Wall Thickness, in.		0.018							
Thermal Treatment		1100 F/20 min/AC				(mill annealed)			
Test Temperature, F		75	600	800	1000	75	600	800	1000
Mechanical									
F_{tu}, ksi	L	133	100	88	58	108	72	67	43
	LT								
	ST								
F_{ty}, ksi	L	121	90	70	32	88	48	56	28
	LT								
	ST								
F_{cy}, ksi	L								
	LT								
	ST								
F_{su}, ksi	L								
	LT								
	ST								
F_{bru}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
F_{bry}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
e, percent in 2.0 in.	L	9	8	12	34	20	18	18	55
	LT								
	ST								

TABLE 51. TYPICAL PROPERTY DATA FOR Ti-3Al-8V-6Cr-4Mo-4Zr

Structural Form (Source)		Tube-Reduced Tubing (8)					
Section or Wall Thickness, in.		0.042					
Thermal Treatment		None	1050/6hrs/AC	1350/6hrs/AC	1250-1550/30min/AC	(a)	(b)
Test Temperature, F		75					
Mechanical							
F_{tu}, ksi	L	168-177	188-196	129-131	126-147	175-178	129-137
	LT						
	ST						
F_{ty}, ksi	L	161-173	179-184	127-128	124-140	161-165	124-131
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 2.0 in.	L	9-10	13-15	22	14-28	10-11	25
	LT						
	ST						

(a) 1500F/30 min/AC
950F/6 hrs/AC

(b) 1500F/30 min/AC
1250F/6 hrs/AC

TABLE 52. TYPICAL PROPERTY DATA FOR Ti-3Al-8V-6Cr-4Mo-4Zr

Structural Form (Source)		Tube Reduced Tubing (8)			Extruded and Tube Reduced (9)				
Section or Wall Thickness, in.		0.025 - 0.042			0.036 -0.375	0.036			
Thermal Treatment		1500 F/ 1.5 hrs / VC			1500 F/15 min/AC	(a)	(b)	(c)	(d)
Test Temperature, F		75	450	650	75				
Mechanical									
F_{tu}, ksi	L	126-137	104-108	97-103	122-134	205	141	177	133
	LT								
	ST								
F_{ty}, ksi	L	121-131	99-103	88-91	120-132	191	136	163	127
	LT								
	ST								
F_{cy}, ksi	L								
	LT								
	ST								
F_{su}, ksi	L								
	LT								
	ST								
F_{bru}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
F_{bry}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
e, percent in 2.0 in.	L	12-23	15-28	20-30	14-25	4	17	11	25
	LT								
	ST								

(a) 1500 F/15 min/AC plus 900F/6 hrs/AC
(b) 1500 F/15 min/AC plus 1250F/6 hrs/AC
(c) 1500 F/30 min/AC plus 950F/6 hrs/AC
(d) 1500 F/30 min/AC plus 1250F/6 hrs/AC

TABLE 53. TYPICAL PROPERTY DATA FOR Ti-4Al-3Mo-1V

Structural Form (Source)		Extruded and Drawn Shapes (10)					
Section or Wall Thickness, in.		Not given					
Thermal Treatment		As Extruded		1250 F/2 hrs/AC		1550/10 Sec/AC	(a)
Test Temperature, F		75	1000	75	1000	75	
Mechanical							
F_{tu}, ksi	L	130-137	90	137-153	95	132-137	184-188
	LT	136		136			
	ST						
F_{ty}, ksi	L	122-136	79	122-141	81	114-122	154-156
	LT	114		113			
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 1.0 in.	L	12-15	23	10-14	16	11-14	4
	LT						
	ST						

(a) 1650F/5 min/WQ
950F/4 hrs/AC

TABLE 54. CONDENSED DESIGN PROPERTY DATA FOR Ti-5Al-2.5Sn

Structural Form (Source)		Extruded Shapes (1)
Section or Wall Thickness, in.		≤ 4.00
Thermal Treatment		1400 - 1600 F/ 10-60 min/AC
Test Temperature, F		75
		(S values)
Mechanical		
F_{tu}, ksi	L	115 - 120
	LT	
	ST	
F_{ty}, ksi	L	110 - 115
	LT	
	ST	
F_{cy}, ksi	L	
	LT	
	ST	
F_{su}, ksi	L	
	LT	
	ST	
F_{bru}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
F_{bry}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
e, percent in 2.0 in.	L	6 - 10
	LT	
	ST	

TABLE 55. TYPICAL PROPERTY DATA FOR Ti-5Al-2.5Sn

Structural Form (Source)		Extruded and Tube-Reduced Tubing (11)				
Section or Wall Thickness, in.		0.16		0.052 - 0.069		
Thermal Treatment		As Extruded	1450-1550 F/2 hrs/AC	1300-1400F/2hrs/AC		
Test Temperature, F		75			600	
Mechanical						
F_{tu}, ksi	L	130	112 - 116	123 - 124	93 - 94	
	LT					
	ST					
F_{ty}, ksi	L	117	104 - 109	105 - 106	70 - 71	
	LT					
	ST					
F_{cy}, ksi	L					
	LT					
	ST					
F_{su}, ksi	L					
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
e, percent in 2.0 in.	L	7	14 - 16	19 - 22	20 - 21	
	LT					
	ST					

TABLE 56. CONDENSED DESIGN PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded Shapes (1)		Extruded Sahpes (?)			
Section or Wall Thickness, in.		< 4.00		≤ 3.00	3.00-4.00	≤ 1.00	1.00-4.00
Thermal Treatment		1300 F/1 hr/AC	(a)	1350F/2 hrs/AC		(b)	
Test Temperature, F		75		75			
		(S Values)		(A&B Values)	(S Values)	(A&B Values)	(S Values)
Mechanical							
F_{tu}, ksi	L	130	130-160	130-137	130	147-163	130-140
	LT			130-139	130	144-163	130-140
	ST						
F_{ty}, ksi	L	120	120-150	118-124	120	133-147	120-130
	LT			120-128	120	130-147	120-130
	ST						
F_{cy}, ksi	L			124-132	126	142-157	128-139
	LT			126-131	126	139-157	128-139
	ST						
F_{su}, ksi	L			84-89	84	89-99	79-85
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L			216-228	216	240-256	204-220
	LT						
	ST						
(e/D=2.0)	L			268-282	268	295-327	261-281
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L			179-188	182	201-222	182-196
	LT						
	ST						
(e/D=2.0)	L			212-223	216	233-257	210-228
	LT						
	ST						
e, percent in 2.0 in.	L	10	6	10	10	6	6
	LT						
	ST						

(a) 1700 F/1 hr/WQ plus 1000F/3 hrs/AC
(b) 1725F/10 min/WQ plus 1000F/4 hrs/AC

TABLE 57. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded Shapes (12)					
Section or Wall Thickness, in.		0.30					0.56
Thermal Treatment		1300 F/40-60 Min/AC					
Test Temperature, F		-110	75	400	600	800	75
Mechanical							
F_{tu}, ksi	L	172-179	140-147	110-113	100-103	93-96	140-144
	LT	169-172	140-150	109-111	102-103	93-94	142-144
	ST						
F_{ty}, ksi	L	162-164	123-135	88-94	72-80	73-75	125-130
	LT	160-162	124-133	86-90	78-80	71-72	130-133
	ST						
F_{cy}, ksi	L	171-179	137-142	92-100	78-84	76-79	
	LT	172-176	138-147	95-96	82	77-78	
	ST						
F_{su}, ksi	L	103-108	89-94	75-79	69-72		
	LT		88-95	74-78			
	ST						
F_{bru}, ksi (e/D=1.5)	L		239-247				
	LT						
	ST						
(e/D=2.0)	L	329-332	270-295	204-231	187-218		
	LT		290-308	215-237			
	ST						
F_{bry}, ksi (e/D=1.5)	L		205-217				
	LT						
	ST						
(e/D=2.0)	L	294-296	233-250	186-198	166-174		
	LT		245-266	193-195			
	ST						
e, percent in 1.0 in.	L	12-14	11-18	15-20	16-18	14-19	14
	LT	11-12	11-17	16	16-17	16	14
	ST						

TABLE 58. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded Shapes (10)									
Section or Wall Thickness, in.		0.080				0.095		0.065		0.043	
Thermal Treatment		(a)	(b)	(c)	(d)	(e)	(f)	(e)	(f)	(c)	(d)
Test Temperature, F		75									
Mechanical											
F_{tu}, ksi	L	173-193	187-191	194-198	192-194	166	180-185	159	181-188	175-178	173-187
	LT										
	ST										
F_{ty}, ksi	L	153-175	172-176	182	178-179	119	161-166	118	164-171	159-165	163-173
	LT										
	ST										
F_{cy}, ksi	L										
	LT										
	ST										
F_{su}, ksi	L										
	LT										
	ST										
F_{bru}, ksi (e/D=1.5)	L										
	LT										
	ST										
(e/D=2.0)	L										
	LT										
	ST										
F_{bry}, ksi (e/D=1.5)	L										
	LT										
	ST										
(e/D=2.0)	L										
	LT										
	ST										
e, percent in 1 in.	L	6-12	6-8	6	6-8	13	7-8	12	7-10	5-8	8-10
	LT										
	ST										

(a) 1725 F/2 min/WO - warm stretch 400-450 F/AC
(b) (a) plus 1000 F/4 hrs/AC
(c) 1725 F/2 min/WQ - hot stretch 1000-1025 F/AC
(d) (c) plus 1000 F/hrs/AC
(e) 1725 F/2 min/WQ
(f) (e) plus 1000 F/4hrs/AC

TABLE 59. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded Shapes (10)							
Section or Wall Thickness, in.		0.062						0.048-0.052	
Thermal Treatment		(a)		(b)	(c)		(d)	(e)	(b)
Test Temperature, F		75	1000	75	75	1000	75	75	
Mechanical									
F_{tu}, ksi	L	149-156	91	173-180	148-153	85	169-178	150-155	184
	LT				144-146				
	ST								
F_{ty}, ksi	L	129-141	73	154-162	133-138	66	151-156	131-141	165-167
	LT				125-126				
	ST								
F_{cy}, ksi	L								
	LT								
	ST								
F_{su}, ksi	L								
	LT								
	ST								
F_{bru}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
F_{bry}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
e, percent in 1 in.	L	10-17	22.5	7-10	12-14	19.0	8-12	15	6-8
	LT				9-10				
	ST								

(a) As extruded and straightened
(b) 1725 F/5 min/WQ --- 1000 F/4 hrs/AC
(c) 1300 F/2 hr/AC
(d) 1675 F/5 min/WQ --- F/4 hrs/AC
(e) 1550 F/10 sec/AC

TABLE 60. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded and Drawn Shapes (13)			
Section or Wall Thickness, in.		0.062	0.040		
Thermal Treatment		As extruded	As drawn	(a)	
Test Temperature, F		75			800
Mechanical					
F_{tu}, ksi	L	153-159	160-165	168-179	102-112
	LT				
	ST				
F_{ty}, ksi	L	142-149	147-152	152-161	84-96
	LT				
	ST				
F_{cy}, ksi	L				
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 2.0 in.	L	7-8	5-8	5-11	
	LT				
	ST				

(a) 1650F/20 min/WQ-plus 1100-1150F/4 hrs/AC
(b) 1725F/1 hr/WQ-plus 1000F/1-4 hrs/AC
(c) 1725F/1 hr/WQ-plus 1250F/4 hrs/AC

TABLE 61. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded Shapes (15/16)											
Section or Wall Thickness, in.		0.06 - 3.00				0.21 - 5.30				0.21 - 1.00			
Thermal Treatment		1300F/2 hrs/AC				1725F/1 hr/WQ plus 1000F/4 hrs/AC				1725 F/1 hr/WQ plus 1250F/4hrs/AC			
Test Temperature, F		-65	75	300	500	-65	75	300	500	-65	75	300	500
Mechanical													
F_{tu}, ksi	L	159-161	130-173	116-121	99-114	171-188	155-180	133-145	117-131	165-167	144-168	123-127	104-113
	LT	157-164	139-149	120-124	99-115	178-183	160-177	136-142	118-129	167-170	144-152	128-130	110-115
	ST												
F_{ty}, ksi	L	148-152	120-148	100-104	81-91	159-176	139-172	114-125	94-104	149-159	127-153	103-110	83-91
	LT	147-152	127-137	103-105	78-91	165-169	146-163	116-119	92-101	154-156	132-139	107-112	84-95
	ST												
F_{cy}, ksi	L		129-167	106-115	78-99		145-185	121-131	98-107		141-166	112-113	83-95
	LT		139-151	109-112	87-100		160-177	121-129	102-115		133-152	113-118	97-98
	ST												
F_{su}, ksi	L		91-103	84-37	67-78		100-112	92-94	76-90		98-104	89	72-85
	LT		94-101	- -	73-77		94-108	- -	81-86		98-103	--	76-82
	ST												
F_{bru}, ksi (e/D=1.5)	L		228-249	198-204	169-188		255-283	222-230	196-217		232-253	210-212	177-194
	LT		233-248	- -	188		263-268	- -	- -		234-254	- -	- -
	ST												
(e/D=2.0)	L		296-313	245-270	212-239		325-351	274-284	231-274		29[illegible]-319	262-266	224-244
	LT		291-317	- -	238-242		333-350	- -	- -		291-32[illegible]	- -	- -
	ST												
F_{bry}, ksi (e/D=1.5)	L		193-209	159-173	132-155		220-250	189-194	167-189		200-222	169-177	140-159
	LT		198-217	- -	149		233-238	- -	- -		190-21[illegible]	- -	- -
	ST												
(e/D=2.0)	L		230-244	188-203	158-179		266-288	203-226	192-217		233-249	191-208	162-187
	LT		220-253	- -	171-182		272-282	- -	- -		21[illegible]-2[illegible]1	- -	- -
	ST												
e, percent in 1 - 2 in.	L		9-20				6-17				10-18		
	LT												
	ST												

TABLE 62. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded and Drawn Shapes (17)				Extruded Shapes (12)	Extruded Shapes (18)
Section or Wall Thickness, in.		0.04				0.125 - 0.625	0.06 - 3.00
Thermal Treatment		1325F/ 1.5 hrs / AC				1300F/2 hrs/ AC	1300F / 2 hrs / AC
Test Temperature, F		75	400	700	900	75	75
Mechanical							
F_{tu}, ksi	L	151-158	121-125	106-107	93-95	140-153	137-149
	LT					141-146	136-156
	ST						
F_{ty}, ksi	L	142-149	107-112	87-91	80-82	121-139	123-136
	LT					127-132	127-149
	ST						
F_{cy}, ksi	L	144-150	111-112	96-99	85-87		131-146
	LT						133-170
	ST						
F_{su}, ksi	L	91-95					
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 1 - 2 in.	L	10-12	12	9-10	14-19	11-16	10-17
	LT					14	12-16
	ST						

TABLE 63. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded and Mandrel-Rolled Tubing (19)					
Section or Wall Thickness, in.		0.083		0.02			
Thermal Treatment		As extruded	1350F/1 hr/AC	As-Rolled	1350 F/1 hr/AC		As Rolled
Test Temperature, F		75				600	
Mechanical							
F_{tu}, ksi	L	161	149-153	181	169	121	142
	LT						
	ST						
F_{ty}, ksi	L	151-154	141-149	173	155	97	97
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 2.0 in.	L	7-11	7-11	6	10	10	5
	LT						
	ST						

TABLE 64. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded and Drawn Tubing (7)				Extruded Tubing (20)	Extruded & Tube-Reduced Tubing (21)	
Section or Wall Thickness, in.		0.028				0.020	0.049 -0.095	
Thermal Treatment		1400F/1 hr/FC				1300 F/2 hr/AC	As reduced	1300 F/1 hr/AC
Test Temperature, F		75	600	800	900	75	75	
Mechanical								
F_{tu}, ksi	L	156	100	97	93	140-155	165-182	141-148
	LT							
	ST							
F_{ty}, ksi	L	133	90	83	80	120-136	154-163	126-135
	LT							
	ST							
F_{cy}, ksi	L							
	LT							
	ST							
F_{su}, ksi	L							
	LT							
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 2.0 in.	L	17	6	6	6	8-14	3-4	21-23
	LT							
	ST							

TABLE 65. TYPICAL PROPERTY DATA FOR Ti-6Al-4V

Structural Form (Source)		Extruded and Tube -Reduced Tubing (11)											
Section or Wall Thickness, in.		0.160		0.052 -0.069		0.016 - 0.083				0.020 - 0.055			
Thermal Treatment		As Extruded	1500F/2Hr/AC	1350F/2hrs/AC		1300F/4 hrs/AC				1400 F/4 hrs/AC			
Test Temperature, F		75			600	72	400	600	800	72	400	600	800
		(Range of Test Values)											
Mechanical													
F_{tu}, ksi	L	139-141	133-141	135-146	101-111	138-150	116	109	106	130-132	106	103	93
	LT												
	ST												
F_{ty}, ksi	L	119-128	118-124	119-130	84-106	120-217	96	86	81	111-114	89	74	71
	LT												
	ST												
F_{cy}, ksi	L												
	LT												
	ST												
F_{su}, ksi	L												
	LT												
	ST												
F_{bru}, ksi (e/D=1.5)	L												
	LT												
	ST												
(e/D=2.0)	L												
	LT												
	ST												
F_{bry}, ksi (e/D=1.5)	L												
	LT												
	ST												
(e/D=2.0)	L												
	LT												
	ST												
e, percent in 2 in.	L	13-14	14-17	16-20	15-21	13-19				16-22	21	17	16
	LT												
	ST												

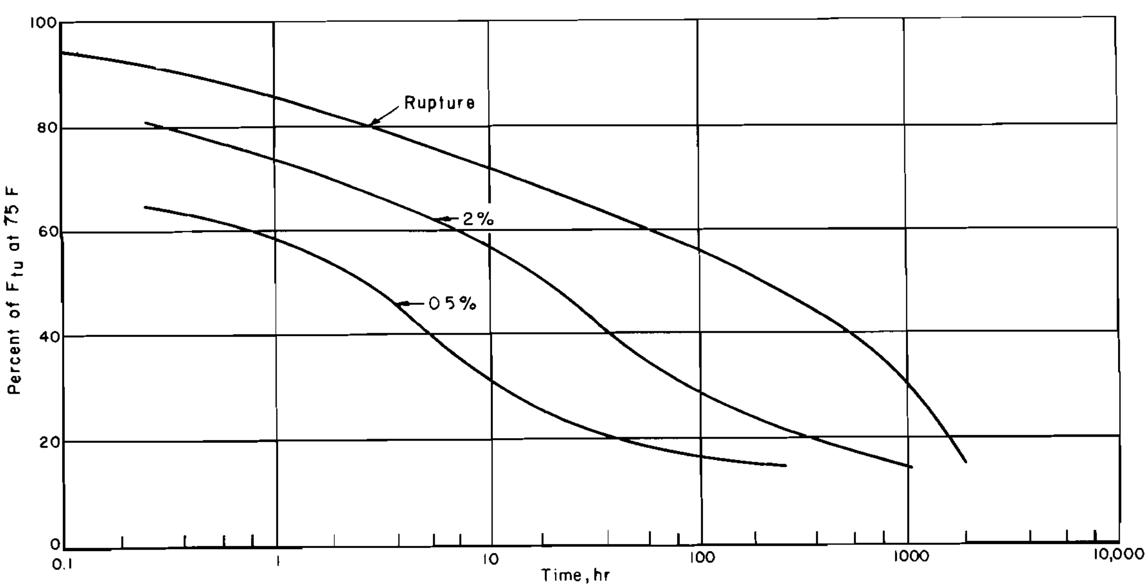

FIGURE 34. CREEP AND STRESS RUPTURE CURVES FOR ANNEALED Ti-6Al-4V AT 900 F

Source (17)

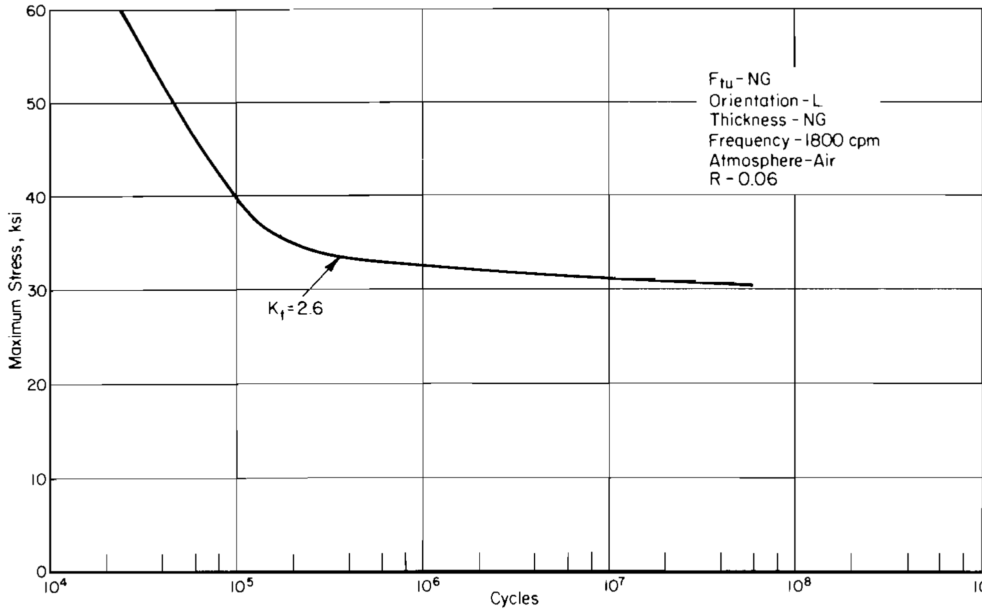

FIGURE 35. AXIAL FATIGUE CURVES FOR ANNEALED AND AGED Ti-6Al-4V AT 75 F

Source (15)

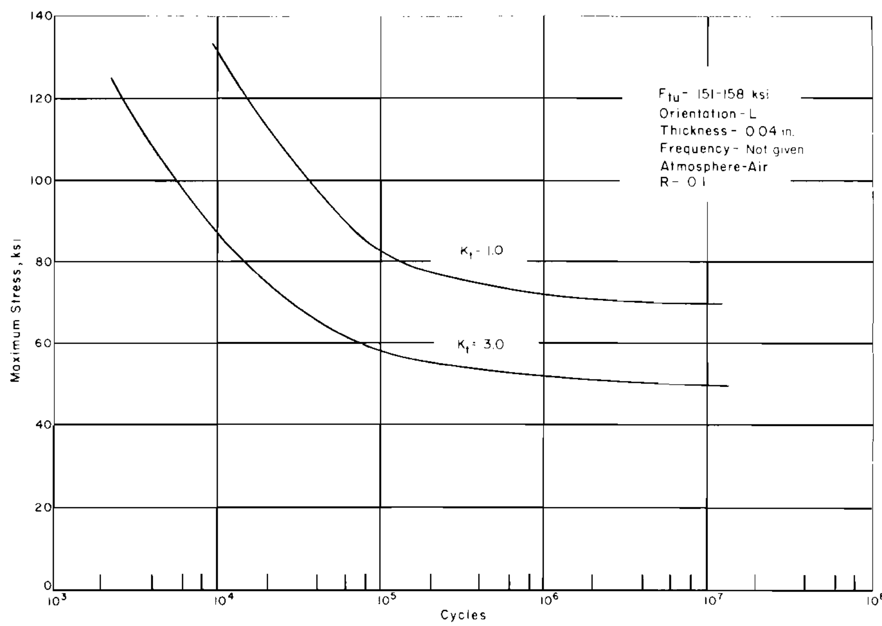

FIGURE 36. AXIAL FATIGUE CURVES FOR ANNEALED Ti-6Al-4V AT 75 F

Source (17)

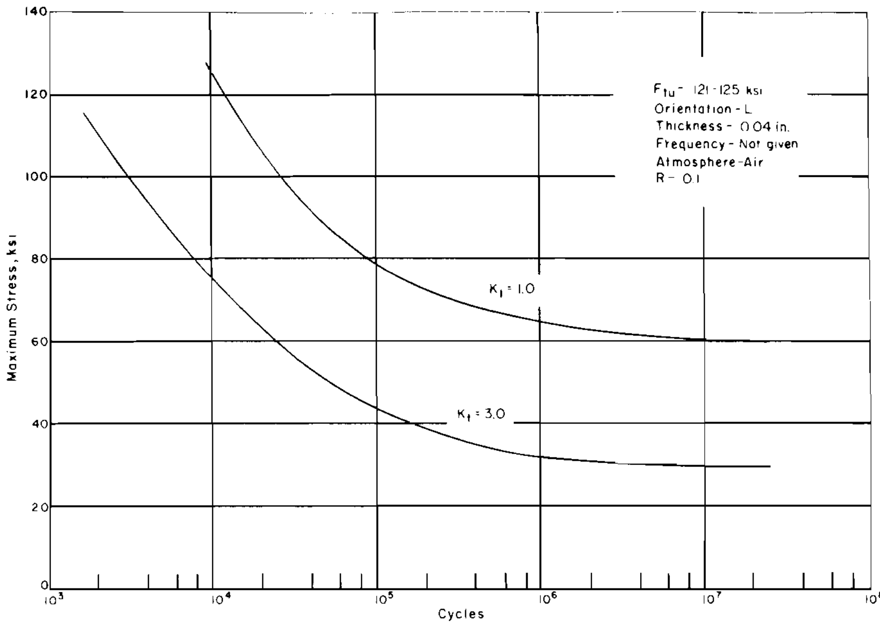

FIGURE 37. AXIAL FATIGUE CURVES FOR ANNEALED Ti-6Al-4V AT 400 F

Source (17)

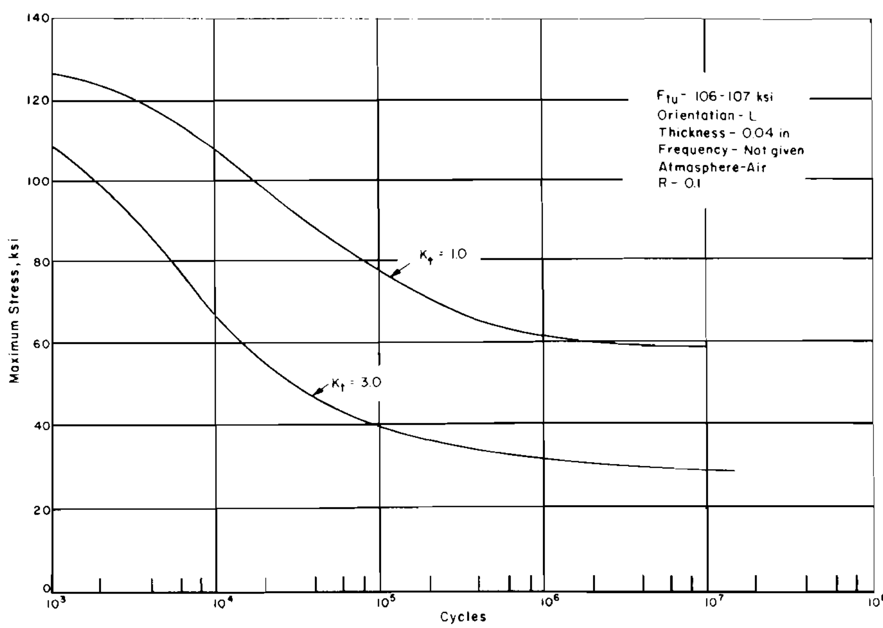

FIGURE 38. AXIAL FATIGUE CURVES FOR ANNEALED Ti-6Al-4V AT 700 F

Source (17)

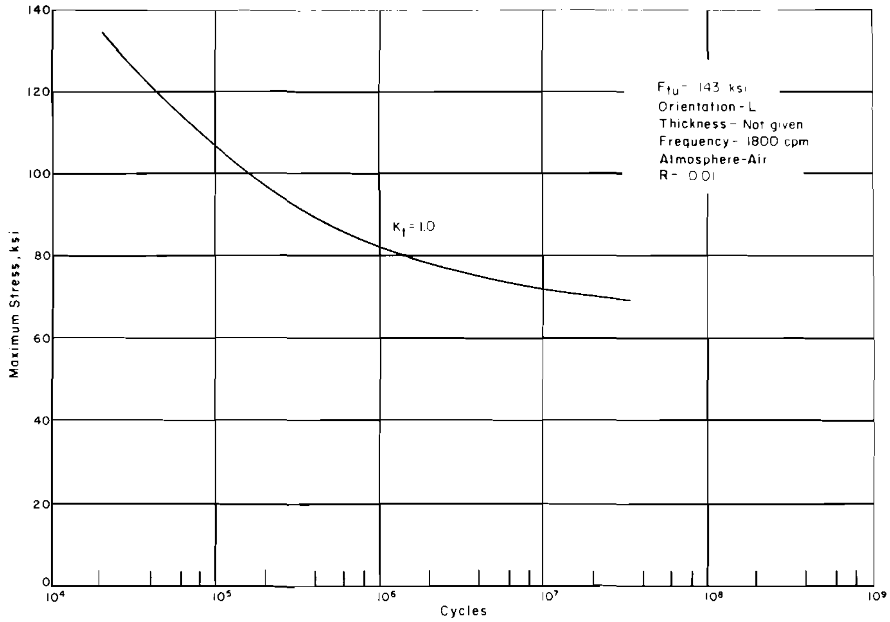

FIGURE 39. AXIAL FATIGUE CURVES FOR ANNEALED Ti-6Al-4V AT 75 F

Source (12)

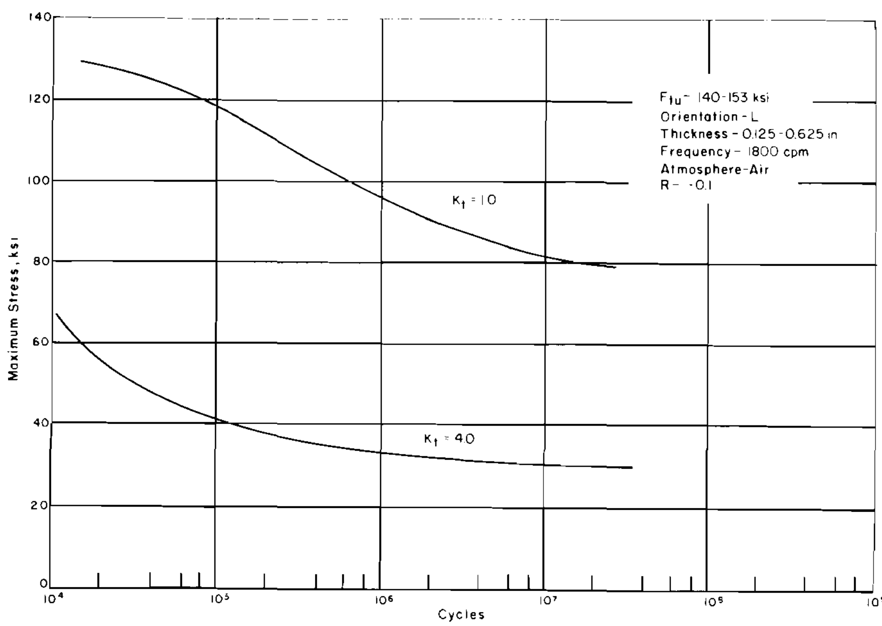

FIGURE 40. AXIAL FATIGUE CURVES FOR ANNEALED Ti-6Al-4V AT 75 F

Source (12)

TABLE 66. CONDENSED DESIGN PROPERTY DATA FOR Ti-6Al-6V-2Sn

Structural Form (Source)	Extruded Shapes (1,2)		
Section or Wall Thickness, in.	≤ 4.00		
Thermal Treatment	1350 F/2 -8 hrs/AC	(a)	
Test Temperature, F	75		
	(S Values)		
Mechanical			
F_{tu}, ksi - - - - - - - - - L	145	150-170	
LT			
ST			
F_{ty}, ksi - - - - - - - - - L	135	140-160	
LT			
ST			
F_{cy}, ksi - - - - - - - - - L			
LT			
ST			
F_{su}, ksi - - - - - - - - - L			
LT			
ST			
F_{bru}, ksi (e/D=1.5) - - - - L			
LT			
ST			
(e/D=2.0) - - - - L			
LT			
ST			
F_{bry}, ksi (e/D=1.5) - - - - L			
LT			
ST			
(e/D=2.0) - - - - L			
LT			
ST			
e, percent in 2.0 in. L	8-10	6	
LT			
ST			

(a) 1650 F/0.5-1 hrs/WQ
1050 F/4-8 hrs/AC

TABLE 67. TYPICAL PROPERTY DATA FOR Ti-6Al-6V-2Sn

Structural Form (Source)	Extruded Shapes (12)						
Section or Wall Thickness, in.	0.30						0.56
Thermal Treatment	1300 F / 40-60 Min / AC						
Test Temperature, F	-110	75	400	600	800		75
Mechanical							
F_{tu}, ksi - - - - - - - - - L	172-190	142-164	125-126	115-121	107-110		154-157
LT	190-193	148-161	132-134	125-127	114-115		160-162
ST							
F_{ty}, ksi - - - - - - - - - L	162-180	131-143	100-105	92-100	86-89		136-142
LT	180-182	133-143	107-108	98-100	91-92		144-148
ST							
F_{cy}, ksi - - - - - - - - - L	182-196	146-156	110-114	101-104	94-97		
LT	199-202	148-161	116-118	105-106	98-103		
ST							
F_{su}, ksi - - - - - - - - - L	118-121	99-104	89-92	80-84			
LT		99-103	86-90				
ST							
F_{bru}, ksi (e/D=1.5) - - - - L		247-274					
LT							
ST							
(e/D=2.0) - - - - L	344-370	287-340	244-260	209-245			
LT		314-344	244-254				
ST							
F_{bry}, ksi (e/D=1.5) - - - - L		218-235					
LT							
ST							
(e/D=2.0) - - - - L	323-335	246-288	216-228	199-208			
LT		255-298	207-231				
ST							
e, percent in 1.0 in. L	9-14	13-21	16-21	16-19	17-24		12-15
LT	9	15-19	14-16	14-15	16-18		11-13
ST							

TABLE 68. TYPICAL PROPERTY DATA FOR Ti-6Al-6V-2Sn

Structural Form (Source)		Extruded Shapes (2)				Extruded Shapes (22)	
Section or Wall Thickness, in.		Not given				0.30 - 0.75	
Thermal Treatment		As Extruded	(a)	(b)	(c)	1300 F/1 hr/AC	(d)
Test Temperature, F						75	
Mechanical							
F_{tu}, ksi	L	170	156	147	140	145-157	171
	LT						
	ST						
F_{ty}, ksi	L	118	143	136	128	123-140	160
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 1 - 2 in.	L	8	12	11	21		
	LT						
	ST						

(a) 1600 F/2 hrs/250 F per hr to 1300 F/AC
900 F/4 hrs/AC
(b) 1700 F/2 hrs/250 F per hr to 1200 F/AC
850 F/8 hrs/AC
(c) 1500 F/1 hr/ 250 F per hr to 1200 F/AC
1000 F/2 hrs/AC
(d) 1550 F/1 hr/WQ
1050 F/4-6 hrs/AC

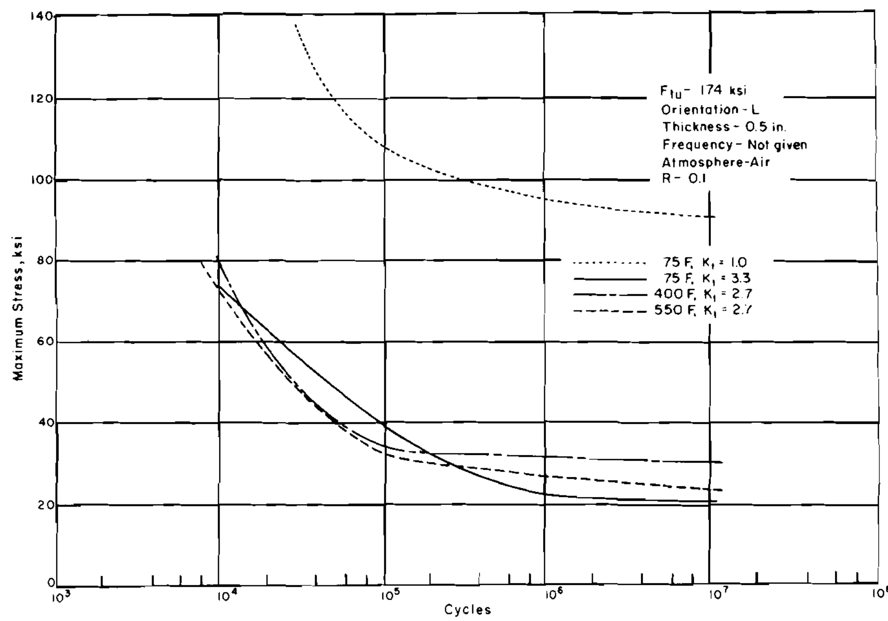

FIGURE 41. AXIAL FATIGUE CURVES FOR AGED Ti-6Al-6V-2Sn

Source (22)

TABLE 69. CONDENSED DESIGN PROPERTY DATA FOR Ti-7Al-4Mo

Structural Form (Source)		Extruded Shapes (1)	
Section or Wall Thickness, in.		≤ 4.00	
Thermal Treatment		1450 F/1 hr/FC to 1050 F/AC	(a)
Test Temperature, F			
		(S Values)	
Mechanical			
F_{tu}, ksi	L	140-145	140-170
	LT		
	ST		
F_{ty}, ksi	L	130-135	130-160
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	10	6
	LT		
	ST		

(a) 1725 F/0.5-1.5 hrs/WQ
1075 F/2-8 hrs/AC

TABLE 70. TYPICAL PROPERTY DATA FOR Ti-7Al-4Mo

Structural Form (Source)		Extruded and Drawn Shapes (10)			
Section or Wall Thickness, in.		0.062			
Thermal Treatment		As Extruded	(a)	(b)	(c)
Test Temperature, F		75			
Mechanical					
F_{tu}, ksi	L	170-184	166-184	186-219	170
	LT	164-168	162-171	180	
	ST				
F_{ty}, ksi	L	140-160	148-165	167-183	157
	LT	144-148	140-149	154	
	ST				
F_{cy}, ksi	L				
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 0.5-1 in.	L	8-11	10-14	3-9	
	LT	4-7	12	3	
	ST				

(a) 1450 F/0.5 hr/FC 100 F per hr to 1000/AC
(b) 1750 F/5 min/WQ plus 1100-1200F/4 hrs/AC
(c) Hot straightened 1550 F/10 sec/AC

TABLE 71. CONDENSED DESIGN PROPERTY DATA FOR Ti-8Al-1Mo-1V

Structural Form (Source)		Extruded Shapes (1)		
Section or Wall Thickness, in.		Not Given		
Thermal Treatment		1450 F/8 hrs/FC	1450 F/8 hrs/FC plus 1450 F/15-20 min/AC	
Test Temperature, F		75	75	
Mechanical				
F_{tu}, ksi	L	120-145	120-130	
	LT			
	ST			
F_{ty}, ksi	L	110-135	110-120	
	LT			
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	10	8-10	
	LT			
	ST			

TABLE 72. TYPICAL PROPERTY DATA FOR Ti-8Al-1Mo-1V

Structural Form (Source)		Extruded Shapes (23)			Extruded Shapes (24)
Section or Wall Thickness, in.		0.125 - 0.70			Not given
Thermal Treatment		1450 F/8 hrs/FC			1450 F/8 hrs/FC plus 1450 F/15 min/AC
Test Temperature, F		-110	75	400	75
Mechanical					
F_{tu}, ksi	L	162	140-150	115	131-134
	LT				
	ST				
F_{ty}, ksi	L	149	127-136	91	114-126
	LT				
	ST				
F_{cy}, ksi	L		142-143		
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 1-2 in.	L	14	10-16	19	10-19
	LT				
	ST				

TABLE 73. TYPICAL PROPERTY DATA FOR Ti-8Al-1Mo-1V

Structural Form (Source)		Extruded Shapes (12)					
Section or Wall Thickness, in.		0.30					0.56
Thermal Treatment		1450 F/40-60 min/AC					
Test Temperature, F		-110	75	400	600	800	75
Mechanical							
F_{tu}, ksi	L	155-170	129-144	105-115	94-108	88-90	132-138
	LT	167-170	132-138	112-114	103-106	93-96	136-138
	ST						
F_{ty}, ksi	L	142-161	114-129	85-89	65-81	62-73	119-126
	LT	159-161	116-123	88-90	78-80	69-72	123-127
	ST						
F_{cy}, ksi	L	162-174	128-140	91-99	77-83	70-78	
	LT	173	132-140	98-100	84	75-80	
	ST						
F_{su}, ksi	L	102-103	86-93	78-79	66-70		
	LT		86-90	75			
	ST						
F_{bru}, ksi (e/D=1.5)	L		213-241				
	LT						
	ST						
(e/D=2.0)	L	323	262-300	212-221	186-199		
	LT		285-326	220-226			
	ST						
F_{bry}, ksi (e/D=1.5)	L		177-203				
	LT						
	ST						
(e/D=2.0)	L	382	218-252	169-189	150-174		
	LT		247-281	190-195			
	ST						
e, percent in 1.0 in.	L	13-16	13-21	18-20	18-23	19-23	12-15
	LT	12	14-17	18	16-20	18-20	13-15
	ST						

TABLE 74. TYPICAL PROPERTY DATA FOR Ti-8Al-1Mo-1V

Structural Form (Source)		Extruded and Drawn Shapes (13)				Form-Rolled Shapes (25)			
Section or Wall Thickness, in.		0.062	0.040			0.05		0.05 -0.10	
Thermal Treatment		As Extruded	As Drawn	(a)		1450F/8 hrs/AC		As Rolled	
Test Temperature, F		75			800	75	850	75	850
Mechanical									
F_{tu}, ksi	L	165-175	173-180	181-197	118-155	135-138	101-103	144-158	102-115
	LT								
	ST								
F_{ty}, ksi	L	144-150	157-169	154-181	104-128	132-133	83-84	130-152	78-112
	LT								
	ST								
F_{cy}, ksi	L								
	LT								
	ST								
F_{su}, ksi	L								
	LT								
	ST								
F_{bru}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
F_{bry}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
e, percent in 1-2 in.	L	7-9	6-7	3-12		7-8	12	10-19	11-20
	LT								
	ST								

(a) 1450F/8 hrs/FC to 800 F/AC

TABLE 75. TYPICAL PROPERTY DATA FOR Ti-8Al-1Mo-1V

Structural Form (Source)		Extruded and Tube-Reduced Tubing (11)				
Section or Wall Thickness, in.		0.16		0.053-0.070		
Thermal Treatment		As Extruded	1600 F/4 hrs/AC	Reduced plus 1600 F/4 hrs/AC		
Test Temperature, F		75			600	
Mechanical						
F_{tu}, ksi	L	148	134-138	134-137	106	
	LT					
	ST					
F_{ty}, ksi	L					
	LT					
	ST					
F_{cy}, ksi	L					
	LT					
	ST					
F_{su}, ksi	L					
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
e, percent in 2 in.	L	10	17-18	25-26	26	
	LT					
	ST					

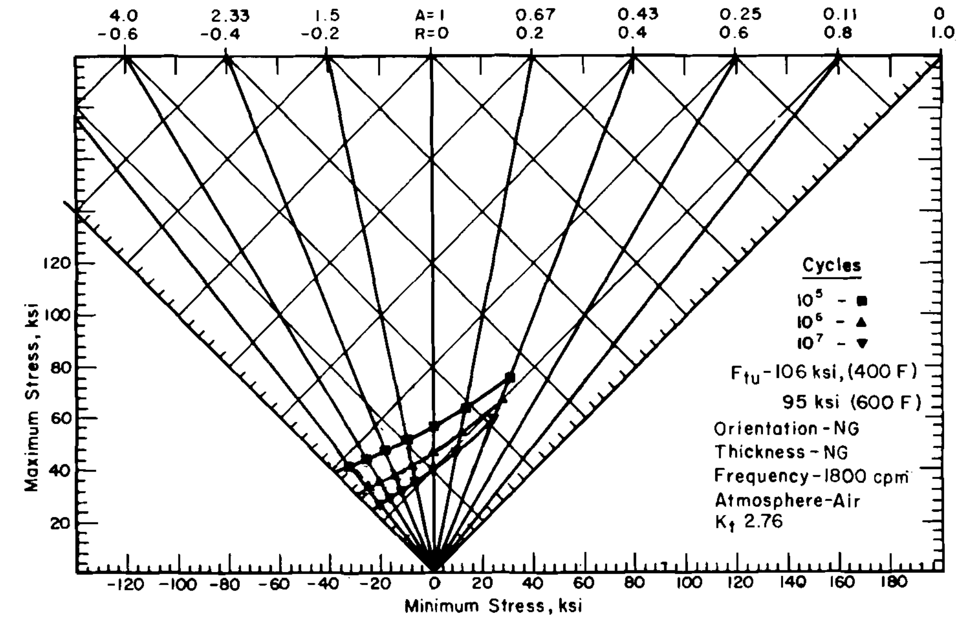

FIGURE 42. AXIAL FATIGUE DATA FOR ANNEALED Ti-8Al-1Mo-1V AT 400 AND 600 F

Source (12)

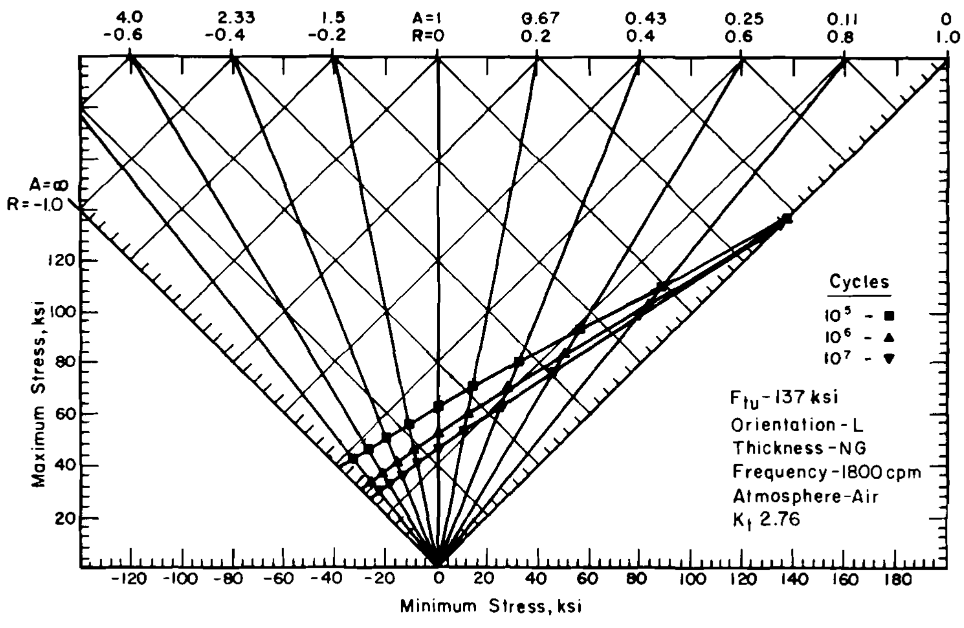

FIGURE 43. AXIAL FATIGUE DATA FOR ANNEALED Ti-8Al-1Mo-1V AT 75 F

Source (12)

TABLE 76. TYPICAL PROPERTY DATA FOR Ti-11.5Mo-6Zr-4.5Sn

Structural Form (Source)		Extruded, Drawn, and Tube-Reduced Tubing (26)								
Section or Wall Thickness, in.		0.173		0.05 - 0.12			0.024			
Thermal Treatment		As Extruded	950 F/8 hrs/AC	(a)	(b)	(c)	As Drawn	(d)	(e)	(f)
Test Temperature, F		75								
Mechanical										
F_{tu}, ksi	L	116-124	200	144	117-131	170-185	162	122	184-189	168
	LT									
	ST									
F_{ty}, ksi	L	100-107	184	135	101-115	160-176	120	111	173-183	150
	LT									
	ST									
F_{cy}, ksi	L									
	LT									
	ST									
F_{su}, ksi	L									
	LT									
	ST									
F_{bru}, ksi (e/D=1.5)	L									
	LT									
	ST									
(e/D=2.0)	L									
	LT									
	ST									
F_{bry}, ksi (e/D=1.5)	L									
	LT									
	ST									
(e/D=2.0)	L									
	LT									
	ST									
e, percent in 2 in.	L	16-18	8	13	14-21	6-9	7	18	5-8	10
	LT									
	ST									

(a) Reduced plus 1350 F/2 hrs/ rapid cool to 900 F/AC
(b) Reduced plus 1350 F/0.5 hr/WO
(c) Condition (a) plus 950-1000 F/8 hrs/AC
(d) Drawn plus 1450 F/0.5 hr/WO
(e) Drawn plus 1350 F/0.5 hr/AC plus 950-1000 F/8 hrs/AC
(f) Drawn plus 1350 F/0.5 hr/AC plus 1050 F/8 hrs/AC

TABLE 77. TYPICAL PROPERTY DATA FOR Ti-13V-11Cr-3Al

Structural Form (Source)		Extruded and Tube-Reduced Tubing (11)				
Section or Wall Thickness, in.		0.160	0.071			
Thermal Treatment		As Extruded	As Reduced	900 F/2 hrs/AC	1400 F/0.5 hr/AC	
Test Temperature, F		75				
Mechanical						
F_{tu}, ksi	L	132	196	209	138	
	LT					
	ST					
F_{ty}, ksi	L	128	185	196	135	
	LT					
	ST					
F_{cy}, ksi	L					
	LT					
	ST					
F_{su}, ksi	L					
	LT					
	ST					
F_{bru}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
F_{bry}, ksi (e/D=1.5)	L					
	LT					
	ST					
(e/D=2.0)	L					
	LT					
	ST					
e, percent in 2 in.	L	19	8	12	30	
	LT					
	ST					

STEEL

STEEL DATA SOURCES

(1) "Metallic Materials and Elements for Aerospace Vehicle Structures", Military Standardization Handbook (MIL-HDBK-5B) September, 1971.

(2) "Aerospace Structurals Handbook — Ferrous Alloys", Volume I, Fourth Revision, March, 1967.

(3) Wilhelm, K. A., "Steel Extrusion Experiments on Air from Components", Lockheed Report No. LR9470, October, 1953.

(4) Christensen, L. M., "Development of Improved Methods, Processes, and Techniques for Producing Steel Extrusions", ML-TDR-64-231, July, 1964.

(5) Scow, A. L. and Dempsey, P. E., "Production Processes for Extruding, Drawing, and Heat Treating Thin Steel Tee Sections", AFML-TR-68-293, October, 1968.

(6) Parikh, N. M., et al., "Final Report on Improved Production of Powder Metallurgy Items", AFML-TR-65-103, March, 1965.

(7) Superior Tube Company, Memo No. 120.

(8) "Unpublished Test Data on Ti-6Al-4V and AM350 Tubing", SST Program, Lockheed Aircraft Corporation, June, 1972.

TABLE 78. SUMMARY OF PHYSICAL AND ELASTIC PROPERTY DATA FOR STEELS AT ROOM TEMPERATURE

Source (1,2)

	Alloy							
Property	8630	H11	18 Ni Maraging (250 Grade)	PH 14-8Mo	PH 15-7Mo	AM 350	410	431
Elastic								
$E_t - 10^6$ psi	29	28-30	26-28	28-29	29	29.4	29-31	29
$E_c - 10^6$ psi	30	30						
$G - 10^6$ psi			10.2		11.4	11.3	12.5	10.5
μ –	0.28	0.28	0.31	0.28	0.28	0.3	0.28	
Physical								
ω – lb/in.^{3}	0.28	0.28	0.29	0.28	0.28-0.30	0.28	0.28	0.28
C – Btu/lb-F[(a)]	0.11	0.11	0.09		0.11	0.11	0.11	0.11
K – Btu-ft/hr/ft^2-F[(b)]	21.7	16.6	15		9.3	9.2	14.4	12
$\alpha - 10^{-6}$ in./in./F[(c)]	6.3	7.4[(e)]	5.6[(d)]	5.3	5-8	6.4	5.5-6.1	5.6

(a) 212 F.
(b) 75 F.
(c) 75 - 212 F.
(d) 75 - 900 F.
(e) 75 - 1200 F.

TABLE 79. TYPICAL PROPERTY DATA FOR 8630

Structural Form (Source)	Extruded Shapes (3)					
Section or Wall Thickness, in.	0.22 -0.32	0.10	0.79	Not given		
Thermal Treatment	(a)			As Extruded	(b)	(c)
Test Temperature, F	75			75		
Mechanical						
F_{tu}, ksi - - - - - - - - - L	188	178	187	91-92	137-138	198-201
LT						
ST						
F_{ty}, ksi - - - - - - - - - L	172	165	178	78-79	127-128	193-194
LT						
ST						
F_{cy}, ksi - - - - - - - - - L						
LT						
ST						
F_{su}, ksi - - - - - - - - - L						
LT						
ST						
F_{bru}, ksi (e/D=1.5) - - - - L						
LT						
ST						
(e/D=2.0) - - - - L						
LT						
ST						
F_{bry}, ksi (e/D=1.5) - - - - L						
LT						
ST						
(e/D=2.0) - - - - L						
LT						
ST						
e, percent in 0.5-1.0 in. L	10	5	15	20-22	15-16	8-10
LT						
ST						

(a) 1550 F/1 hr/OQ
800 F/2 hrs/AC
(b) 1550 F/1 hr/OQ
1100 F/2 hr/AC
(c) 1550 F/1 hr/OQ
800 F/2 hrs/AC

TABLE 80. TYPICAL PROPERTY DATA FOR H 11

Structural Form (Source)	Extruded Shapes (4)	
Section or Wall Thickness, in.	0.033 - 0.084	0.055 - 0.073
Thermal Treatment	(a)	(b)
Test Temperature, F	75	
Mechanical		
F_{tu}, ksi - - - - - - - - - L	213-286	244-269
LT		
ST		
F_{ty}, ksi - - - - - - - - - L	156-233	193-208
LT		
ST		
F_{cy}, ksi - - - - - - - - - L		
LT		
ST		
F_{su}, ksi - - - - - - - - - L		
LT		
ST		
F_{bru}, ksi (e/D=1.5) - - - - L		
LT		
ST		
(e/D=2.0) - - - - L		
LT		
ST		
F_{bry}, ksi (e/D=1.5) - - - - L		
LT		
ST		
(e/D=2.0) - - - - L		
LT		
ST		
e, percent in 2.0 in. L	3-9	5-10
LT		
ST		
Fracture Toughness		
K_C (K_{SCC}), ksi $\sqrt{in.}$ - - - - L		
LT		
ST		

(a) 1875 F/1 hr/AC
1000 F/2 hrs/AC
1000 F/2 hrs/AC
(b) 1850 F/0.5 hr/AC
975 F/3 hrs/AC
975 F/3 hrs/AC
975 F/3 hrs/AC

TABLE 81. TYPICAL PROPERTY DATA FOR 18 Ni (250) MARAGING

Structural Form (Source)		Extruded Shapes (5)							
Section or Wall Thickness, in.		0.06					0.04		
Thermal Treatment		(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Test Temperature, F		75							
Mechanical									
F_{tu}, ksi	L	140-145	220-237	228-242	178	133	156-160	178-187	247-257
	LT								
	ST								
F_{ty}, ksi	L	110-116	204-217	212-222	127	102	151-159	161-178	244-254
	LT								
	ST								
F_{cy}, ksi	L								
	LT								
	ST								
F_{su}, ksi	L								
	LT								
	ST								
F_{bru}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
F_{bry}, ksi (e/D=1.5)	L								
	LT								
	ST								
(e/D=2.0)	L								
	LT								
	ST								
e, percent in 1-2 in.	L	7-10	5-8	5-7	17	10	3-4	5-12	2-3
	LT								
	ST								

(a) As extruded
(b) 900 F/3 hrs/AC
(c) 1500 F/1 hr/AC
900 F/3 hrs/AC
(d) 1150 F/1 hr/AC
(e) 1700 F/1 hr/AC
1500 F/1 hr/AC
(f) As drawn
(g) Straightened at 1100 F
(h) (g) plus 1500 F/30 min/AC
900 F/3 hrs/AC

TABLE 82. TYPICAL PROPERTY DATA FOR PH 14-8 Mo

Structural Form (Source)		Extruded Shapes (5)	
Section or Wall Thickness, in.		0.06	
Thermal Treatment		As Extruded	(a)
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	155-157	226-228
	LT		
	ST		
F_{ty}, ksi	L	98-106	205-214
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 1.0 in.	L	11-13	10-12
	LT		
	ST		

(a) 1825 F/3min/AC
1700 F/30 min/AC
1000 F/8 hrs/AC
950 F/3 hrs/AC

TABLE 83. TYPICAL PROPERTY DATA FOR PH 15-7 Mo

Structural Form (Source)		Extruded Shapes (4)	Extruded Shapes (6)				
Section or Wall Thickness, in.		0.064 - 0.077	0.25				
Thermal Treatment		(a)	As Extruded				
Test Temperature, F		75	75	400	800	1200	1400
Mechanical							
F_{tu}, ksi	L	196-226	245	235	200	145	95
	LT	200-222					
	ST						
F_{ty}, ksi	L	164-208					
	LT	191-212					
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 1-2 in.	L	6-15	13	14	15	17	18
	LT						
	ST						

(a) 1750 F/10 min/WQ
-100 F/8 hrs/AW
950F/1.5 hrs/AC

TABLE 84. TYPICAL PROPERTY DATA FOR PH 15-7 Mo

Structural Form (Source)		Extruded and Drawn Tubing (7)						
Section or Wall Thickness, in.		Not given						
Thermal Treatment		(a)	(b)	(c)	(d)	(e)	(f)	
Test Temperature, F		75						
Mechanical								
F_{tu}, ksi	L	150	155-185	180-220	130-170	165-205	210-250	
	LT							
	ST							
F_{ty}, ksi	L	55-85	85-115	120-180	80-110	155-195	195-235	
	LT							
	ST							
F_{cy}, ksi	L							
	LT							
	ST							
F_{su}, ksi	L							
	LT							
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 2.0 in.	L	30-45	10-25	6-20	3-12	5-12	3-12	
	LT							
	ST							

(a) As extruded No. 1 Temper
(b) As extruded No. 2 Temper
(c) As extruded No. 3 Temper
(d) 1950 F/1 hr/AC
1400 F/1.5 hr/AC
60 F/0.5 hr/AW
(e) (d) plus 1050 F/1.5 hr/AC
(f) 1950 F/1 hr/AC
1750 F/10 min/AC
-100 F/8 hr/AW
950 F/1.5 hr/AC

TABLE 85. TYPICAL PROPERTY DATA FOR AM 350

Structural Form (Source)		Extruded and Tube-Reduced (8)	
Section or Wall Thickness, in.		0.016 - 0.083	
Thermal Treatment		(a)	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	188-211	
	LT		
	ST		
F_{ty}, ksi	L	156-198	
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 2.0 in.	L	20-22	
	LT		
	ST		

(a) Reduced then tempered
700-950 F/3 hrs/AC

TABLE 86. TYPICAL PROPERTY DATA FOR 410

Structural Form (Source)		Extruded Shapes (3)	
Section or Wall Thickness, in.		0.10 - 0.91	
Thermal Treatment		(a)	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	191-205	
	LT	194-200	
	ST		
F_{ty}, ksi	L	156-184	
	LT	156-176	
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 0.5 in.	L	10-24	
	LT	12-21	
	ST		

(a) 1750 F/1 hr/OQ
600 F/2 hrs/AC

TABLE 87. TYPICAL PROPERTY DATA FOR 431

Structural Form (Source)		Extruded Shapes (3)	
Section or Wall Thickness, in.		0.22 - 0.79	
Thermal Treatment		(a)	
Test Temperature, F		75	
Mechanical			
F_{tu}, ksi	L	201-203	
	LT		
	ST		
F_{ty}, ksi	L	135-153	
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 0.5 in.	L	8-17	
	LT		
	ST		

(a) 1900 F/1 hr/OQ
700 F/3 hrs/AC

SUPERALLOYS

SUPERALLOY DATA SOURCES

(1) "Metallic Materials and Elements for Aerospace Vehicle structures", Military Standardization Handbook (MIL-HDBK-5B), September, 1971.

(2) "Aerospace Structural Metals Handbook", Volume II-A, Non-Ferrous Heat Resistant Alloys, Syracuse University Press, Syracuse, N. Y., March, 1967.

(3) "Properties of Some Metal and Alloys", International Nickel Company, Inc., 1968.

(4) "Materials Data Handbook – Inconel Alloy 718", Second Edition, NASA-CR-123774, April, 1972.

(5) "Materials Data Handbook – Alloy A 286", NASA-CR-123776, June, 1972.

(6) Christensen, L. M., "Development of Improved Methods, Processes, and Techniques for Producing Steel Extrusions", July, 1964.

(7) Friedman, G. I., and Lowenstein, P., "Processing Techniques for the Extrusion of Superalloy Powders", AFML-TR-68-321, October, 1968.

(8) "Form Rolling Close Tolerance Shapes of Superalloys", AFMC-TR-69-186, July, 1969.

(9) Parikh, N. M., et al., "Final Report on Improved Production of Powder Metallurgy Items", AFML-TR-65-103, March, 1965.

(10) Doble, G. S., "Manufacturing Techniques for the Extrusion of Superalloy Structural Shapes", AFML-TR-68-325, October, 1968.

(11) Gorecki, T. A. and Friedman, G. I., "Extruded Structural Shapes from Superalloy Powders", ASM-SME Paper W71-5.4, 1971 Western Metal and Tool Conference and Exposition, March, 1971.

(12) Barnett, W. J. and Peterson, E. V., "A Manufacturing Process for Small Diameter Bar and Extruded Shapes of TD Nickel-Chromium", AFML-TR-68-117, May, 1968.

(13) Peterson, E. V., "Development of a Tubing and Bar Process for a Dispersion-Strengthened Ni-Cr-ThO_2 Alloy", AFML-TR-67-364, November, 1967.

TABLE 88. SUMMARY OF PHYSICAL AND ELASTIC PROPERTY DATA FOR SUPERALLOYS AT ROOM TEMPERATURE

(Sources 1, 2, 3, 4, 5)

	Alloy								
Property	A 286	B 1900	Hastelloy X	713 C	718	René 41	TD Ni-Cr	U 700	Waspaloy
Elastic									
E_t – 10^6 psi	29.1	31.0	28.6	29.9	29.0-29.6	31.9		32-34	30.6
E_c – 10^6 psi	29.1		29			31.6			
G – 10^6 psi	10.4				11.4	12.1			
μ –	0.30				0.28	0.31			
Physical									
ω – lbs/in.^{3}	0.286	0.297	0.297	0.289	0.297	0.298		0.286	0.296
C – Btu/lb-F[(a)]	0.11		0.12		0.104	0.11		0.14	0.13
K – Btu-ft/hr/ft^2-F[(b)]	7.0	5.9	5.3	12.2	6.6	5.2		11.3	6.1
α – 10^{-6}in./in-F[(c)]	9.2	6.5	7.7	5.9	7.1-7.3	6.6		7.7	6.8

(a) 212 F.
(b) 75 F.
(c) 75 - 212 F.

TABLE 89. TYPICAL PROPERTY DATA FOR A-286

Structural Form (Source)		Drawn Tubing (1)	Drawn Tubing (5)
Section or Wall Thickness, in.		Not Given	Not Given
Thermal Treatment		1800 F/1 hr/OQ plus 1325 F/16 hrs/AC[a]	1800 F/1 hr/WQ
Test Temperature, F		75	75
		(Range of S Values)	
Mechanical			
F_{tu}, ksi	L	130-140	110
	LT		
	ST		
F_{ty}, ksi	L	85-95	35-60
	LT		
	ST		
F_{cy}, ksi	L	85-95	
	LT		
	ST		
F_{su}, ksi	L	85-91	
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L	195-210	
	LT		
	ST		
(e/D=2.0)	L	247-266	
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L	127-142	
	LT		
	ST		
(e/D=2.0)	L	153-171	
	LT		
	ST		
e, percent in 2.0 in.	L	12-15	25-50
	LT		
	ST		

(a) Higher values are for consumable-electrode melted material.

TABLE 90. TYPICAL PROPERTY DATA FOR A-286

Structural Form (Source)		Drawn Tubing (5)					Extruded Shapes (6)
Section or Wall Thickness, in.		0.028					0.06
Thermal Treatment		1800 F/2 hrs/WQ plus 1325F/16 hrs/AC					1650 F/2 hrs/OQ plus 1325 F/16 Hrs/AC
Test Temperature, F		75	400	800	1200	1600	75
Mechanical							
F_{tu}, ksi	L	163	160	147	100	15	128-133
	LT						
	ST						
F_{ty}, ksi	L	100	100	98	57	7	84-92
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 2.0 in.	L	22	30	28	10	30	[illegible]
	LT						
	ST						

TABLE 91. TYPICAL PROPERTY DATA FOR A-286

Structural Form (Source)		Extruded Shapes (5)		
Section or Wall Thickness, in.		Not Given		
Thermal Treatment		(a)	(b)	(c)
Test Temperature, F		75		
Mechanical				
F_{tu}, ksi	L	162	149	150
	LT	131	147	131
	ST			
F_{ty}, ksi	L	120	86	85
	LT	105	89	83
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	29	25	26
	LT	27	24	15
	ST			

(a) 1800 F/2 hrs/WQ
1325 F/16 hrs/AC
(b) 1650 F/2 hrs/WQ
1300 F/16 hrs/AC
(c) 1750 F/2 hrs/WQ
1300 F/16 hrs/AC

TABLE 92. TYPICAL PROPERTY DATA FOR B1900

Structural Form (Source)		Extruded Shapes (7)	
Section or Wall Thickness, in.		0.10	
Thermal Treatment		(a)	
Test Temperature, F		75	1400
Mechanical			
F_{tu}, ksi	L	145-167	113
	LT		
	ST		
F_{ty}, ksi	L	143-165	113
	LT		
	ST		
F_{cy}, ksi	L		
	LT		
	ST		
F_{su}, ksi	L		
	LT		
	ST		
F_{bru}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
F_{bry}, ksi (e/D=1.5)	L		
	LT		
	ST		
(e/D=2.0)	L		
	LT		
	ST		
e, percent in 1.0 in.	L	3-5	2
	LT		
	ST		

(a) 2200 F/4 hrs/AC
1975 F/4 hrs/AC
1550 F/4 hrs/AC
1400 F/16 hrs/AC

TABLE 93. TYPICAL PROPERTY DATA FOR HASTELLOY X

Structural Form (Source)		Form Rolled Shapes (8)		
Section or Wall Thickness, in.		0.05		
Thermal Treatment		1950 F/ 15 min/FC		
Test Temperature, F		75	1200	1800
Mechanical				
F_{tu}, ksi	L	122	90	13
	LT			
	ST			
F_{ty}, ksi	L	68	52	10
	LT			
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	20	30	57
	LT			
	ST			

TABLE 94. TYPICAL PROPERTY DATA FOR 713 C

Structural Form (Source)		Extruded Shapes (9)					
Section or Wall Thickness, in.		0.25					
Thermal Treatment		None					
Test Temperature, F		75	400	800	1200	1600	2000
Mechanical							
F_{tu}, ksi	L	198	198	198	185	160	95
	LT	183-192					
	ST						
F_{ty}, ksi	L						
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in in.	L						
	LT						
	ST						

TABLE 95. CONDENSED DESIGN PROPERTY DATA FOR 718

Structural Form (Source)		Drawn Tubing (1)		Extruded Shapes (10)	
Section or Wall Thickness, in.		> 0.015		0.31-0.47	
Thermal Treatment		(a)	(b)	(a)	
Test Temperature, F		75		75	1200
		(Range of S Values)			
Mechanical					
F_{tu}, ksi	L	185	170	189-193	156-158
	LT				
	ST				
F_{ty}, ksi	L	150	145	162-167	133-137
	LT				
	ST				
F_{cy}, ksi	L				
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 2.0 in.	L	12	15	22-25	16-20
	LT				
	ST				

(a) 1775 F/1 hr/AC
1325 F/8 hrs/FC at 100 F per hr
1150 F/8 hrs/AC

(b) 1950 F/1 hr/AC
1400 F/8 hrs/FC at 100 F per hr
1200 F/8 hrs/AC

TABLE 96. TYPICAL PROPERTY DATA FOR 718

Structural Form (Source)		Extruded Shape (11)	Form-Rolled Shapes (8)		
Section or Wall Thickness, in.		Not Given	0.5 - 1.0		
Thermal Treatment		2000-2200 F/4 hrs/AC	1950 F/15 min/FC		
Test Temperature, F		1200	75	1200	1400
Mechanical					
F_{tu}, ksi	L	150-158	195	150	115
	LT				
	ST				
F_{ty}, ksi	L	125-132	170	135	100
	LT				
	ST				
F_{cy}, ksi	L				
	LT				
	ST				
F_{su}, ksi	L				
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L				
	LT				
	ST				
e, percent in 2.0 in.	L	16-28	23	19	10
	LT				
	ST				

TABLE 97. TYPICAL PROPERTY DATA FOR RENÉ 41

Structural Form (Source)	Form-Rolled Shapes (8)		
Section or Wall Thickness, in.	0.05		
Thermal Treatment	2200 F/15 min/AC		
Test Temperature, F	75	1200	1700
Mechanical			
F_{tu}, ksi - - - - - - - - - L	165	155	50
LT			
ST			
F_{ty}, ksi - - - - - - - - - L	122	115	42
LT			
ST			
F_{cy}, ksi - - - - - - - - - L			
LT			
ST			
F_{su}, ksi - - - - - - - - - L			
LT			
ST			
F_{bru}, ksi (e/D=1.5) - - - - L			
LT			
ST			
(e/D=2.0) - - - - L			
LT			
ST			
F_{bry}, ksi (e/D=1.5) - - - - L			
LT			
ST			
(e/D=2.0) - - - - L			
LT			
ST			
e, percent in 2.0 in. L	16	15	24
LT			
ST			

TABLE 98. TYPICAL PROPERTY DATA FOR TD Ni-Cr

Structural Form (Source)	Extruded Shapes (12)		Extruded and Drawn Tubing (13)	
Section or Wall Thickness, in.	0.1		0.012 - 0.188	
Thermal Treatment	2400 F/2 hrs/AC		2000-2400 F/ 1 hr/AC	
Test Temperature, F	75	2000	75	2000
Mechanical				
F_{tu}, ksi - - - - - - - - - L	86-122	6-15	118-146	6-17
LT				
ST				
F_{ty}, ksi - - - - - - - - - L			73-108	5-17
LT				
ST				
F_{cy}, ksi - - - - - - - - - L	57-78	5-14		
LT				
ST				
F_{su}, ksi - - - - - - - - - L				
LT				
ST				
F_{bru}, ksi (e/D=1.5) - - - - L				
LT				
ST				
(e/D=2.0) - - - - L				
LT				
ST				
F_{bry}, ksi (e/D=1.5) - - - - L				
LT				
ST				
(e/D=2.0) - - - - L				
LT				
ST				
e, percent in 2.0 in. L	19-32	14-25	19-30	2-11
LT				
ST				

TABLE 99. TYPICAL PROPERTY DATA FOR U 700

Structural Form (Source)		Extruded Shapes (7)		Extruded Shapes (9)				
Section or Wall Thickness, in.		0.14 - 0.15		0.25				
Thermal Treatment		(a)		none				
Test Temperature, F		75	1400	75	400	800	1200	1600
Mechanical								
F_{tu}, ksi	L	184-217	149-164	245	245	230	215	135
	LT							
	ST							
F_{ty}, ksi	L	145-162	112-133					
	LT							
	ST							
F_{cy}, ksi	L							
	LT							
	ST							
F_{su}, ksi	L							
	LT							
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 1.0 in.	L	12-17	8-14	6	7	8	11	15
	LT							
	ST							

(a) 2200 F/4 hrs/AC
1975 F/4 hrs/AC
1550 F/4 hrs/AC
1440 F/4 hrs/AC

TABLE 100. TYPICAL PROPERTY DATA FOR WASPALOY

Structural Form (Source)		Extruded Shapes (10)
Section or Wall Thickness, in.		0.28-0.41
Thermal Treatment		1975 F Cool to 1550 F/24 hrs/AC plus 1400 F/16 hrs/AC
Test Temperature, F		75
Mechanical		
F_{tu}, ksi	L	170-176
	LT	
	ST	
F_{ty}, ksi	L	104-110
	LT	
	ST	
F_{cy}, ksi	L	
	LT	
	ST	
F_{su}, ksi	L	
	LT	
	ST	
F_{bru}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
F_{bry}, ksi (e/D=1.5)	L	
	LT	
	ST	
(e/D=2.0)	L	
	LT	
	ST	
e, percent in 2.0 in.	L	29-32
	LT	
	ST	

REFRACTORY METALS AND ALLOYS

REFRACTORY METAL SOURCES

(1) "Aerospace Structural Metals Handbook", Volume II Non-Ferrous Alloys, Syracuse University Press, Syracuse, N. Y., March, 1967.

(2) "Properties of Some Metals and Alloys", International Nickel Company, Inc., 1968.

(3) "Materials Selector – 1972", *Materials Engineering,* Vol. 74, No. 4, September, 1972.

(4) Hicks, R. H., Unpublished Preliminary Data, Universal Cyclops Steel Corporation, undated.

(5) Parikh, N. M., et al., "Final Report on Improved Production of Powder Metallurgy Items", AFML-TR-65-103, March, 1965.

(6) Peterson, E. V., et al., "Final Report on Columbium and Columbium Alloy Extrusion Program", ASD-TDR-63-637, Vol II, August, 1963.

(7) Peterson, E. V., "Small Diameter, Thin-Walled Columbium Tubing Program", AFML-TR-66-306, September, 1966.

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(9) Huber, R., Randall, R., and Sawyer, H., "Final Report on Development of Advanced Techniques for the Fabrication of Refractory Metal Tubing", AFML-TR-65-341, October, 1965.

TABLE 101. SUMMARY OF PHYSICAL AND ELASTIC PROPERTY DATA FOR REFRACTORY METALS AND ALLOYS AT ROOM TEMPERATURE

(Source 1, 2, 3)

Property	Metal or Alloy			
	Unalloyed Molybdenum	TZM	D43	Cb752
Elastic				
E_t – 10^6 psi	46.0	46.0	18.0	15.0
E_c – 10^6 psi				
G – 10^6 psi	17.4			
μ –	0.31 - 0.32			
Physical				
ω – lb/in.^{3}	0.369	0.369	0.33	0.326
C – Btu/lb-F[(a)]	0.06	0.06	0.06[(d)]	0.06
K – Btu-ft/hr/ft^2-F[(b)]	75 - 85	81 - 85	35[(d)]	22[(d)]
α – 10^{-6} in./in.-F[(c)]	2.7	3.0	4.3[(e)]	3.8

(a) 212 F.
(b) 75 F.
(c) 75 - 212 F.
(d) 500 F.
(e) 1000 - 2500 F.

TABLE 102. TYPICAL PROPERTY DATA FOR UNALLOYED MOLYBDENUM

Structural Form (Source)		Extruded Tubing (4)					
Section or Wall Thickness, in.		2.125					
Thermal Treatment		None	1700 F/0.5 hr/VC	1900 F/0.5 hr/VC	2100 F/0.5 hr/VC	2300 F/0.5 hr/VC	2600 F/0.5 hr/VC
Test Temperature, F		75					
Mechanical							
F_{tu}, ksi	L	87	89	84	70	71	71
	LT	90	92	87		69	63
	ST						
F_{ty}, ksi	L	79	86	81	60	58	55
	LT	87	89	87		59	54
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 0.5 in.	L	10	7	7	13	13	10
	LT	1	1	1	-	6	2
	ST						

TABLE 103. TYPICAL PROPERTY DATA FOR TZM

Structural Form (Source)		Extruded Shapes (6)		
Section or Wall Thickness, in.		0.25		
Thermal Treatment		None		
Test Temperature, F		75	1200	1800
Mechanical				
F_{tu}, ksi	L	138	98	74
	LT			
	ST			
F_{ty}, ksi	L			
	LT			
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 1.0 in.	L	6	10	8
	LT			
	ST			

TABLE 104. TYPICAL PROPERTY DATA FOR D 43

Structural Form (Source)		Tube-Reduced Tubing (6)	Tube-Reduced and Drawn Tubing (7)	
Section or Wall Thickness, in.		0.018-0.062	0.015 - 0.03	
Thermal Treatment		2200/0.5 hr/VC	2300/0.5 hr/VC	
Test Temperature, F		75	75	2200
Mechanical				
F_{tu}, ksi	L	83-99	67-74	25-30
	LT			
	ST			
F_{ty}, ksi	L	56-80	41-49	23-27
	LT			
	ST			
F_{cy}, ksi	L			
	LT			
	ST			
F_{su}, ksi	L			
	LT			
	ST			
F_{bru}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
F_{bry}, ksi (e/D=1.5)	L			
	LT			
	ST			
(e/D=2.0)	L			
	LT			
	ST			
e, percent in 2.0 in.	L	26-38	28-45	34-47
	LT			
	ST			

TABLE 105. TYPICAL PROPERTY DATA FOR D 43

Structural Form (Source)		Extruded and Drawn Shapes (8)					
Section or Wall Thickness, in.		0.25		0.04			
Thermal Treatment		None	2200 F/1 hr/VC	None	2200F/1 hr/VC		
Test Temperature, F		75				2200	2700
Mechanical							
F_{tu}, ksi	L	68-75	69	85-86	70-74	31-32	12-14
	LT						
	ST						
F_{ty}, ksi	L	51-57	42-50	80-83	54-59	28-31	10-11
	LT						
	ST						
F_{cy}, ksi	L						
	LT						
	ST						
F_{su}, ksi	L						
	LT						
	ST						
F_{bru}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
F_{bry}, ksi (e/D=1.5)	L						
	LT						
	ST						
(e/D=2.0)	L						
	LT						
	ST						
e, percent in 2.0 in.	L	3-15	23-27	7	22-24	27-32	52-61
	LT						
	ST						

TABLE 106. TYPICAL PROPERTY DATA FOR Cb752

Structural Form (Source)		Extruded and Drawn Shapes (8)						Drawn Tubing (9)
Section or Wall Thickness, in.		0.25		0.04				0.010 - 0.020
Thermal Treatment		None	2500 F/1 hr/AC	None	2500 F/1 hr/AC			None
Test Temperature, F		75				2200	2700	75
Mechanical								
F_{tu}, ksi	L	62-69	65-67	91-97	74-77	29-30	13-14	110-113
	LT							
	ST							
F_{ty}, ksi	L	51-53	50-51	89-90	54-57	24-25	13-14	97-101
	LT							
	ST							
F_{cy}, ksi	L							
	LT							
	ST							
F_{su}, ksi	L							
	LT							
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 2.0 in.	L	23-31	27-32	10	20-25	31	48-56	3-6
	LT							
	ST							

BERYLLIUM

BERYLLIUM DATA SOURCES

(1) "Metallic Materials and Elements for Aerospace Vehicle Structures", Military Standardization Handbook (MIL-HDBK-5B), September, 1971.

(2) "Aerospace Structural Metals Handbook", Vol. II Non-Ferrous Metals, Syracuse University Press, Syracuse, N. Y., March, 1967.

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TABLE 107. SUMMARY OF PHYSICAL AND ELASTIC PROPERTY DATA FOR BERYLLIUM AND BERYLLIUM ALLOYS AT ROOM TEMPERATURE
(Source 1,2)

Property	Alloy: Unalloyed Beryllium	Alloy: Lockalloy
Elastic		
E_t – 10^6 psi	42.5	29.0
E_c – 10^6 psi	42.5	–
G – 10^6 psi	20.0	13.0
μ –		
Physical		
ω – lbs/in^3	0.066	0.076
C – Btu/lb-F[(a)]	0.45	0.39
K – Btu-ft/hr-ft^2-F[(b)]	104	118-123
α – 10^{-6} in/in-F[(c)]	6.4	9.0

(a) 212 F.
(b) 75 F.
(c) 75 – 212 F.

TABLE 108. TYPICAL PROPERTY DATA FOR UNALLOYED BERYLLIUM

Structural Form (Source)		Extruded Tubing (3)	Extruded Tubing (4)					
Section or Wall Thickness, in.		0.02 - 0.04	0.33					
Thermal Treatment		None	None					
Test Temperature, F		75	75	200	400	600	800	1000
Mechanical								
F_{tu}, ksi	L	78-89	95	97	89	66	49	40
	LT		58	63	63	58	49	40
	ST							
F_{ty}, ksi	L	41-53	50	53	49	41	37	30
	LT		50	51	49	45	41	32
	ST							
F_{cy}, ksi	L	38-45						
	LT							
	ST							
F_{su}, ksi	L							
	LT							
	ST							
F_{bru}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
F_{bry}, ksi (e/D=1.5)	L							
	LT							
	ST							
(e/D=2.0)	L							
	LT							
	ST							
e, percent in 1.0 in.	L	5-9	7-11	20	31	37	37	22
	LT		1	2	3	5	17	11
	ST							

TABLE 109. TYPICAL PROPERTY DATA FOR LOCKALLOY

Structural Form (Source)		Extruded Shapes (5)	Extruded Tubing (3)		Extruded Tubing (6)
Section or Wall Thickness, in.		Not Given	0.02		Not Given
Thermal Treatment		1100 F/24 hrs/AC	1100 F/24 hrs/AC		None
Test Temperature, F		75	75		75
Mechanical					
F_{tu}, ksi	L	46-52	81-86	53-60	62
	LT	32-37			
	ST				
F_{ty}, ksi	L	34-38	79-81	49-50	46
	LT	30-35			
	ST				
F_{cy}, ksi	L	32-35	71-78	43-56	
	LT	29-33			
	ST				
F_{su}, ksi	L	22-24			
	LT				
	ST				
F_{bru}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L	74-82			
	LT				
	ST				
F_{bry}, ksi (e/D=1.5)	L				
	LT				
	ST				
(e/D=2.0)	L	65-72			
	LT				
	ST				
e, percent in 1.0 in.	L	6	<1	2-5	1
	LT	1			
	ST				

SECTION 4

SUMMARY OF COMPETITIVE PROCESSES

by

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SECTION 4

SUMMARY OF COMPETITIVE PROCESSES

INTRODUCTION

Several processes are or may become economical alternatives to extrusion or form rolling in fabricating aircraft structural shapes and tubing. These competitive processes are described in detail in Part II, Section 4. So that the designer may be able to review these processes quickly, the important aspects of each of these processes – their advantages, limitations, and production potential – are summarized here:

The data sheets which follow cover the processes as listed below:

Brake Bending or Forming
Rubber Pad Forming
Roll Forming
Hydrostatic Extrusion (Warm and Cold Processing)
Extrusion of Powders to Shapes
High-Frequency Resistance Welding
Diffusion Bonding
Rolling With Heated Rolls

COMPETITIVE PROCESS -- BRAKE BENDING OR FORMING

Process Description

Bending flat stock over a radiused form block to produce long, narrow parts with a single curvature on cross section.

Process Characteristics

Advantages

Equipment widely available, low tooling costs, versatile, can be done warm, some applicability for all materials.

Limitations

For simple linear shapes. Production rates relatively low; large bend radii for titanium and hard aluminum alloys.

Current Production Usage for Aircraft Manufacturing

Yes, especially for parts 4 to 12 feet long with bends spaced 6 inches or more apart and for small quantities of smaller parts.

Production Potential

In use.

COMPETITIVE PROCESS – RUBBER PAD FORMING

Process Description

Rubber pad acts like a fluid to exert a fairly uniform pressure to press the workpiece around a solid form block.

Process Characteristics

Advantages

Rubber pad replaces many dies; fewer and simpler tools than conventional pressing processes, thinning less pronounced and cracking less likely than with metal tooling.

Limitations

Limiting forming pressure quite low; rubber wears out, wrinkling common on stretch flanges. More expensive than brake or press forming for long runs, less suited to elevated temperatures, lengths less than 4 feet.

Current Production Usage for Aircraft Manufacturing

Widely used for straight and curved flanges and bending.

Production Potential

In use.

COMPETITIVE PROCESS – ROLL FORMING

Process Description

Produces shapes by feeding and bending strip or sheet lengthwise through a series of contoured rolls.

Process Characteristics

Advantages

Easy to automate; good versatility to shape materials; auxiliary operations such as notching and piercing can be incorporated; close tolerances.

Limitations

Equipment expensive; setup time is long; roll sets have to be designed and built for each shape; comparatively few companies equipped or experienced for handling aircraft materials.

Current Production Usage for Aircraft Manufacturing

Small, if any, except for stainless steel or aluminum.

Production Potential

Good where mass production of specific shapes and products are required.

COMPETITIVE PROCESS – EXTRUSION OF POWDERS TO SHAPES

Process Description

A composite billet of metal powder and shaped components of a sacrificial filler material is extruded to rounds; then the filler is removed chemically or mechanically to obtain the desired shape.

Process Characteristics

Advantages

Complex shapes can be made; suitable equipment relatively available; larger reductions and better shape definition possible than with conventional extrusion.

Limitations

Billet preparation and disassembly operations are tedious and expensive; powders of suitable quality and composition not always readily available; production experience is limited.

Current Production Usage for Aircraft Manufacturing

Prototype production only.

Production Potential

Good for complex shapes with variations in section thickness and re-entrant angles. Applications to superalloys appear most promising.

COMPETITIVE PROCESS – HYDROSTATIC EXTRUSION (WARM AND COLD PROCESSING)

Process Description

Utilizes pressurized lubricant/fluid system around billet during extrusion. Pressurized system prevents billet upsetting and eliminates container friction.

Process Characteristics

Advantages

Reduced extrusion pressure requirements. Good surface finishes and dimensional control. Greater throughput/push due to use of long billets.

Limitations

High pressures required. Tool life with warm extrusion is not defined. Reduced extrusion ratios with cold processing.

Current Production Usage for Aircraft Manufacturing

None – in developmental stages.

Production Potential

Very good for thin-wall tubing and for hard aluminum alloys in simple shapes through greatly increased production rates.

COMPETITIVE PROCESS – HIGH-FREQUENCY RESISTANCE WELDING

Process Description

Flat or shaped strip is heated by resistance and pressure welded in the solid state to form simple shapes.

Process Characteristics

Advantages

High speed process readily automated for high production; welding equipment widely available.

Limitations

Special tooling must be added to commercial facilities; development work needed for some materials, shapes, and sections; necessity for inspecting joints in products.

Current Production Usage for Aircraft Manufacturing

Not used but in advanced state of development.

Production Potential

Good for large quantities of simple shapes in thin sections.

COMPETITIVE PROCESS – DIFFUSION BONDING

Process Description

Pressure bonding at elevated temperatures in the solid state with minimal deformation primarily by pressing, rolling or extrusion.

Process Characteristics

Advantages

Applicable to variety of metals, product size, combinations of materials, and specialized products; bending temperatures often low enough to retain superior microstructures and properties of components.

Limitations

Requires some specialized equipment, preparation and design of assemblies is difficult; production experience and equipment limited to relatively few organizations.

Current Production Usage
for Aircraft Manufacturing

Limited production.

Production Potential

Very high for a variety of parts and products.

COMPETITIVE PROCESS – ROLLING WITH HEATED ROLLS

Process Description

To minimize forming loads and chilling of workpiece surfaces, rolls are heated to or near the temperature of bar or billet feed stock.

Process Characteristics

Advantages

Reduces tendencies for cracking in brittle materials such as tungsten and beryllium; permits rolling to thinner sections or tighter radii, or using lighter equipment.

Limitations

Requires novel equipment; processes are in early stage of development; best suited to producing large quantities of identical shapes.

Current Production Usage
for Aircraft Manufacturing

None; only experimental equipment available.

Production Potential

Good, particularly for superalloys, other high-strength materials.

PART II

MANUFACTURING METHODS FOR STRUCTURAL SHAPES AND TUBING

SECTION 1

EXTRUSION PRACTICES FOR STRUCTURAL SHAPES

by

Thomas G. Byrer

SECTION 1

EXTRUSION PRACTICES FOR STRUCTURAL SHAPES

INTRODUCTION

Section 1 discusses the extrusion process and the many interrelated factors which must be considered in defining extrusion conditions for a production environment. The history of extrusion is reviewed briefly and the two major extrusion techniques used for all metals today are described. The unlubricated extrusion method is used with aluminum alloys, and glass-lubricated extrusion for all high-temperature materials of interest to the aircraft and aerospace industry.

Extrusion data sheets are included for various high-temperature alloys which have been extruded into aircraft structural shapes. These data sheets contain information published in the open literature and in Air Force reports but do not contain detailed data on extrusion conditions for all metals and alloys of interest to the Air Force. Much of this information is considered proprietary by commercial extruders and practices of individual extruders vary.

History and Background

"Hot extrusion" as defined here means that a cylindrical billet has been heated to a temperature between the recrystallization and melting temperatures and forced by compressive load on one end to flow through the aperture of a suitably shaped die positioned at the opposite end. The product, which is continuous, has a smaller cross-sectional area than that of the starting billet. Extruded sections produced by hot extrusion are fabricated by what is called the "direct extrusion process", in which the ram entering the extrusion container and applying pressure to the back of the extrusion billet is moving in the same direction as the billet material and the exiting material.

The invention of the extrusion process is generally credited to Joseph Bramah, who was granted a patent in 1797 for a press to be used to make lead pipe. This press forced liquid lead through an orifice around the mandrel; lead solidifying in the orifice was extruded by the force applied to the liquid lead. The process was improved in the early 1800's by Burr[1] and Hansen[1] whose use of a lead billet essentially invented the direct extrusion process.

Almost 100 years later (in 1894), Alexander Dick successfully extruded a copper alloy. This represents a significant advancement in the development of the extrusion process since the presses available for lead and cable extrusion could not extrude copper alloys without heating the metals to elevated temperatures. Until his death in 1903, Alexander Dick continued to improve his extrusion process and originated the horizontal extrusion press, an insulated and multiple-wall container, fixed and floating mandrels, and electrically heated containers. As Pearson[1] indicates in his historical survey, ". . . although radical changes in design and accessory equipment have taken place in the last 60 years, present extrusion presses embody the principles discovered by Dick".

Concurrently, two other innovations were realized. Later merging, they produced a major market for extruded products which remains extremely important today. Hall was inventing a practical process for producing metallic aluminum in 1886, and the Wright Brothers, in 1909, were solving the problem of man's ability to sustain flight in a heavier-than-air vehicle. As aircraft construction began in earnest for commercial transportation and for war-time use in World War I, the advantages of lightweight aluminum became increasingly apparent.

The Duralumin alloys were first used in aircraft construction. Figure 1 shows the framework of a large airship built principally of extruded and drawn duralumin sections[2]. In the 1920's and 1930's, aluminum was used more and more, and the onset of World War II saw widespread use of both extruded components and other wrought forms in the construction of military aircraft.

The trend has continued, and aluminum alloys are used almost exclusively in today's aircraft manufacture. Figure 2 shows a variety of extruded sections available in the 1930's for aircraft manufacture, Figure 3 shows other larger and more complex shapes now used in the age of the jumbo jet.

The next major step in the development of the extrusion process came in the late 1940's and 1950's with the advent of the jet age and the potential for air travel at supersonic speeds. Analysis of aircraft design showed that higher strength materials and those with better elevated-temperature strength properties would be needed if these aircraft were to be successful. Thus derived the age of high-temperature extrusion development of such

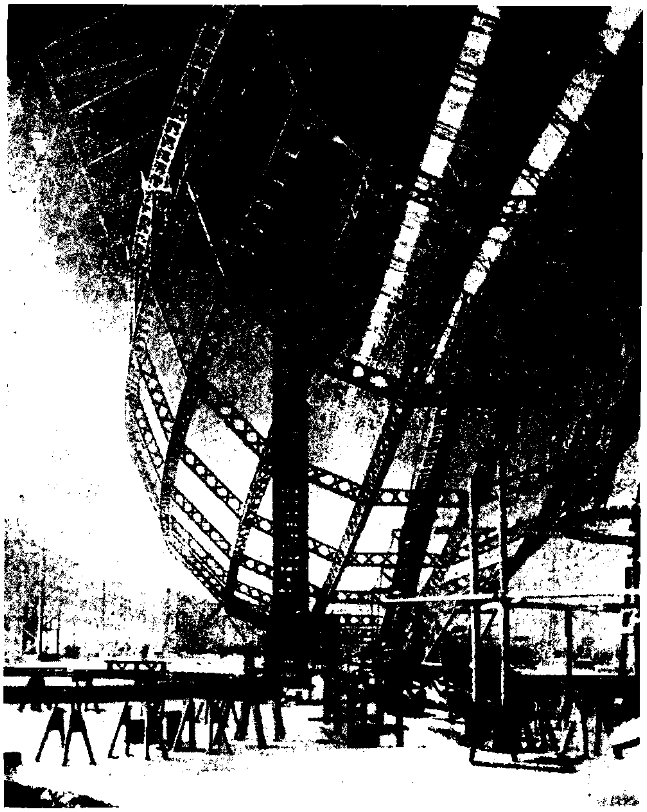


FIGURE 1. CONSTRUCTION OF R100 LIGHTER-THAN-AIR CRAFT USING DURALUMIN EXTRUDED AND DRAWN SECTIONS[2]

FIGURE 2. TYPICAL SECTIONS IN ALUMINUM AND ALUMINUM ALLOYS AVAILABLE IN THE 1930'S[2]

materials as steel, titanium, refractory metals, beryllium, and superalloys.

Of paramount importance to the success of these developments was Mr. Jacques Sejournet's patent in 1944 for the use of glass as an extrusion lubricant. While steels had been extruded extensively in World War II and the immediate postwar period, no good lubrication techniques existed for the extrusion of steels in long lengths at temperatures above about 1600 F. Short lengths could be extruded if tooling were cooled between cycles, but today's 20 to 30-foot extrusions became a production reality as a result of the glass-lubrication extrusion process.

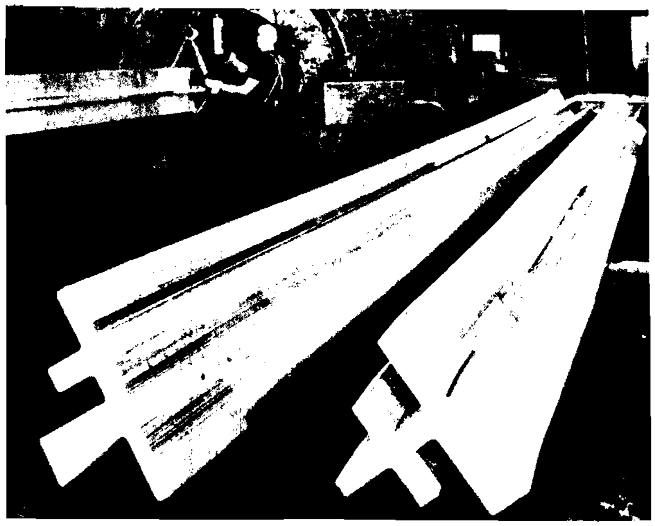


FIGURE 3. 7075 ALUMINUM ALLOY EXTRUDED RIB CHORDS USED IN THE BOEING 747 AIRCRAFT[5]

Work in the late 1940's in France with this new extrusion technique developed production methods for extruding steel tubing which are now licensed in over two dozen industrial plants around the world. Figure 4 shows hot-extruded, shaped steel tubing made by the Sejournet glass process.[4] The development of this new extrusion technique and the new material requirements for aircraft led the U.S. Air Force Materials Laboratory to undertake an extensive series of manufacturing process development programs for extruding aircraft structural shapes in a variety of high-strength materials. These programs, conducted in U.S. industrial facilities, represent an investment of over $12,000,000 from 1950 to 1965 in developing extrusion procedures. This technology for hot extrusion of high-temperature materials has continued to advance over the past 10 years and many alloys are extruded routinely today.

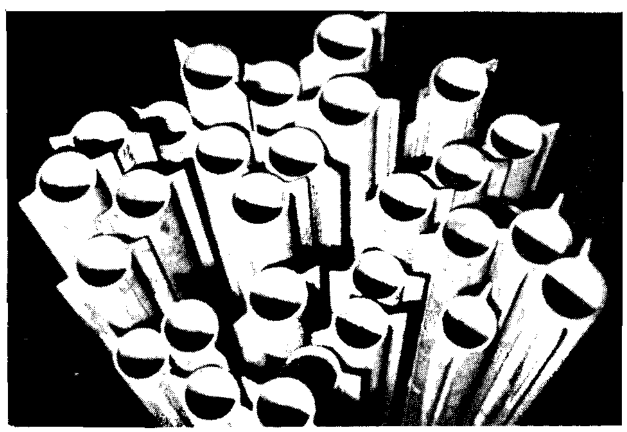


FIGURE 4. FINNED STEEL TUBING HOT EXTRUDED WITH THE SEJOURNET GLASS LUBRICATION PROCESS

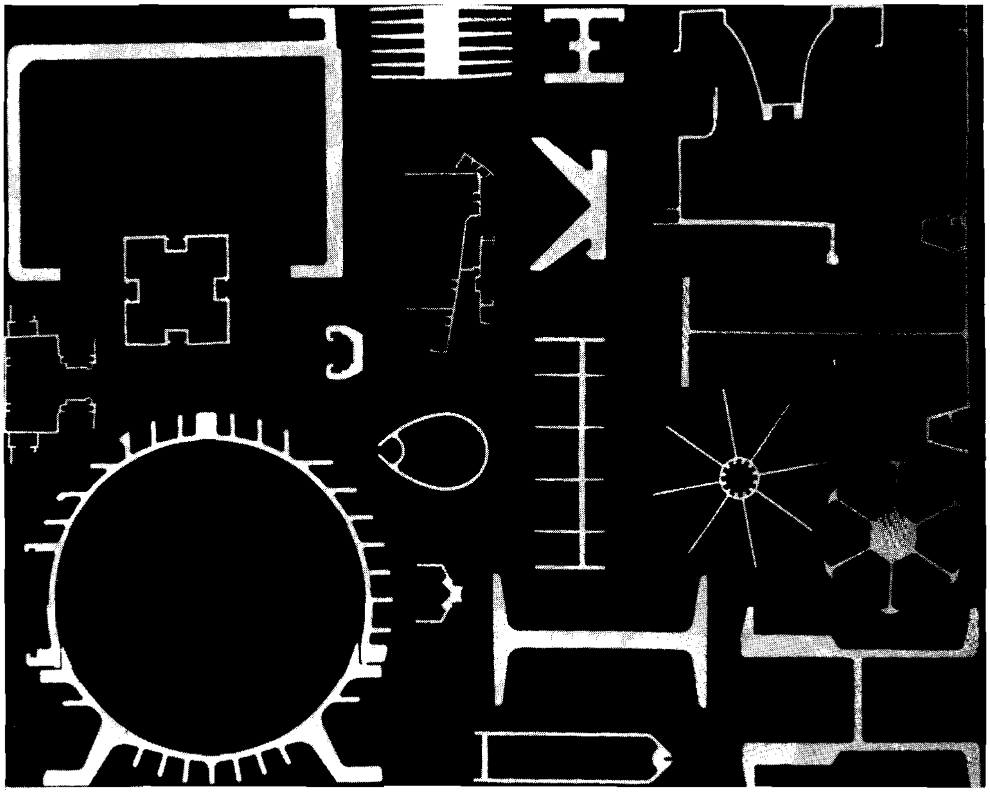


FIGURE 5. TYPICAL EXTRUDED SHAPES MANUFACTURED IN ALUMINUM AND ALUMINUM ALLOYS

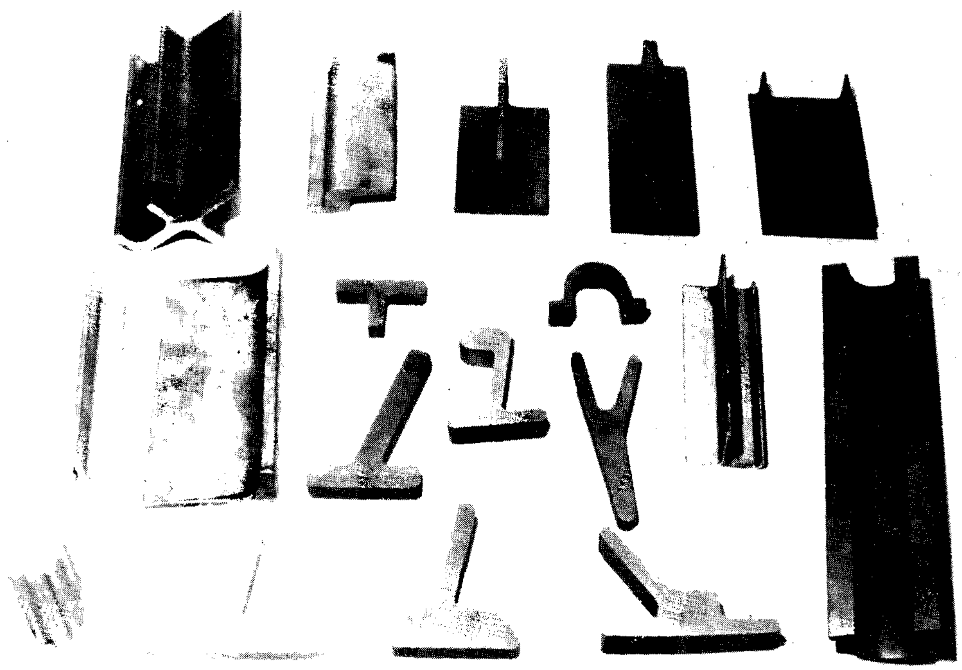


FIGURE 6. SECTIONS OF TYPICAL TITANIUM ALLOY HOT EXTRUDED STRUCTURAL SHAPES

Development of the extrusion process is not dormant; Air Force Materials Laboratory support in the area continues. Efforts are under way to study isothermal extrusion processes aimed at eliminating the problems of billet chilling which occurs with current techniques.[5] Conventional hot-extrusion methods are continually upgraded as new generations of titanium alloys are developed.[6] Hydrostatic extrusion, an old process first studied in 1933, is on the threshold of becoming a commercial process by virtue of AFML-sponsored programs continuing from the 1960's.[7] In industry, the indirect-extrusion process, invented in the early 1800's, is again being considered for extruding high-strength aluminum alloys. Thus, advancements in a process, now almost 200 years old, can be expected to continue as man's understanding of metals and their behavior continues to grow and new technologies make new and different demands on available materials in the years ahead.

Requirements for Aircraft Manufacture

Extruded shapes have been used in aircraft manufacture beginning with airship fabrication in the 1920's and continuing through the development of war-time piston-engine aircraft, commercial jet aircraft, and military high-speed, high-performance aircraft. The term "extruded shapes" has referred primarily to such configurations as T-, Z-, H-, L-, and ⅃⊓L sections. These simple shapes, in a multitude of sizes and section thicknesses, are the basic configurations used originally in aircraft construction and have been basically retained in modern day designs.

Many variations of these shapes are also used in specific applications. The unique ability of the extrusion process to produce a wide complexity of configurations has been its key to success. Because the capability for shape complexity is related primarily to material strength, extrusion-process conditions are dictated by the strength factor. As material strength increases, the complexity and configurations possible in an extruded shape generally become more limited. Figure 5 shows complex shapes of aluminum alloys; Figure 6, less complex configurations possible with the much higher strength titanium alloys.

Aluminum Alloys

Since most aircraft are basically of aluminum construction, the variety of extruded products used is quite extensive. Simple shapes are used extensively as stringers and stiffeners for both wing and fuselage construction. These shapes are generally basic configurations (T-, Z-, L-, etc.). Shapes of this type used in the Concorde supersonic aircraft construction are shown in Figure 7.

FIGURE 7. ALUMINUM ALLOY EXTRUSIONS UTILIZED IN THE CONCORDE SUPERSONIC AIRCRAFT[8]

Alloy – Hiduminium-RR.58.

In contrast, large aluminum extrusions play an important part in the manufacture of the large jumbo jets flown in commercial travel. Figure 8 shows large wing carrythrough structures which are now widely used in aircraft manufacture. Also shown is an integrally stiffened panel that, in modern-day designs, eliminates the need for attaching an extruded T-section to a flat plate to make a stiffened section. Extrusion techniques now allow sections of this type to be extruded as an integral piece. These are used primarily in wing construction although the Soviets have curved extruded panels for use as fuselage sections.[9]

The center extrusion in Figure 8 is a stepped aluminum extrusion used in aircraft construction. This application is for the wing carry-through area with the thicker section located in the area where the wing attaches to the fuselage.

Figures 9 and 10 show shape complexity to be realized with aluminum extrusion. Figure 9 shows extruded landing mat sections which were widely used for the construction of air fields during the Viet Nam conflict. Figure 10 shows an integrally stiffened truss core section proposed for aircraft-droppable bridge construction and other commercial load-carrying applications where lightweight structures are desired.

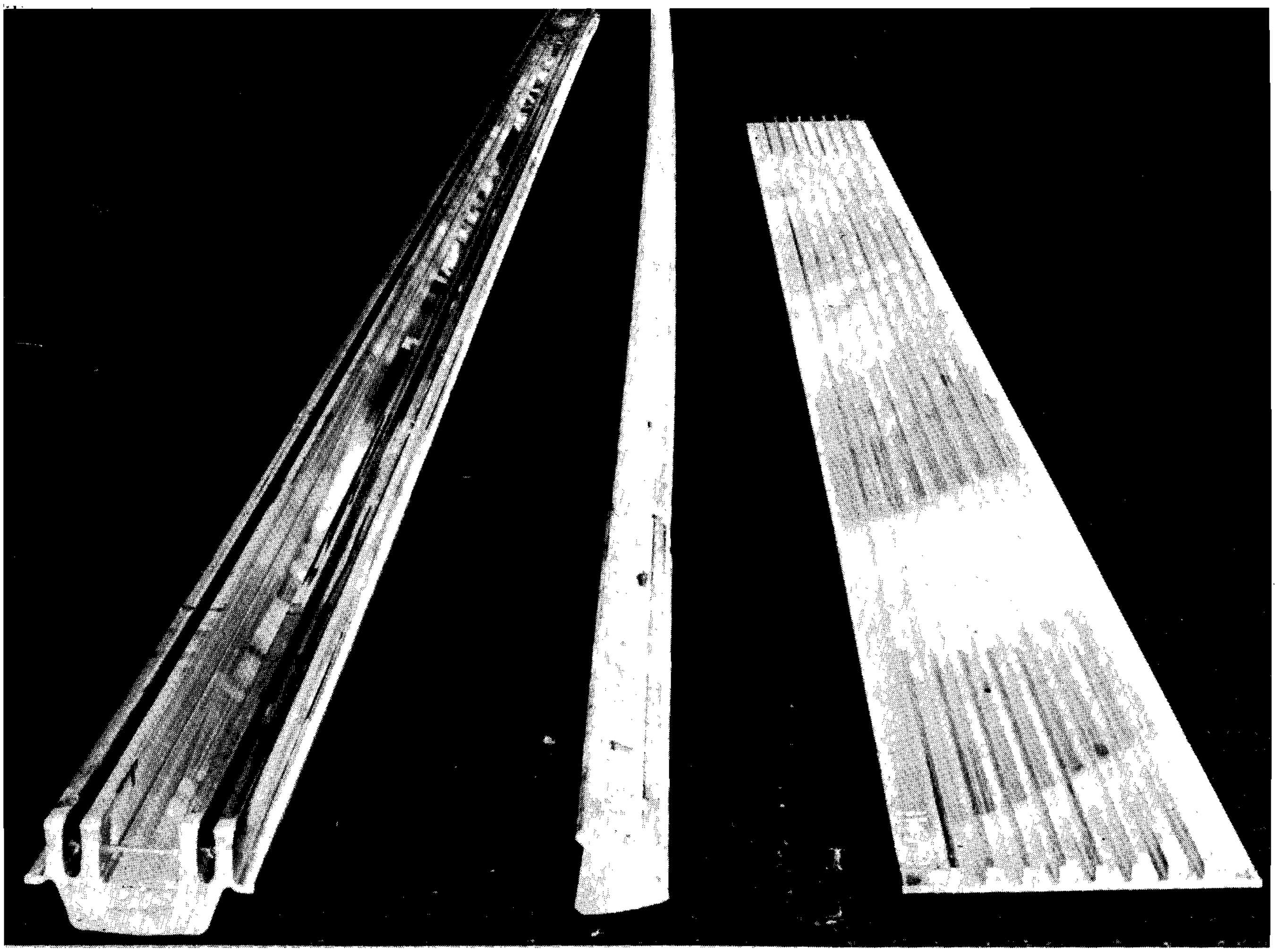


FIGURE 8. ALUMINUM ALLOY WING CARRYTHROUGH, STEPPED, AND INTEGRALLY STIFFENED PANEL EXTRUSIONS USED IN AIRCRAFT CONSTRUCTION

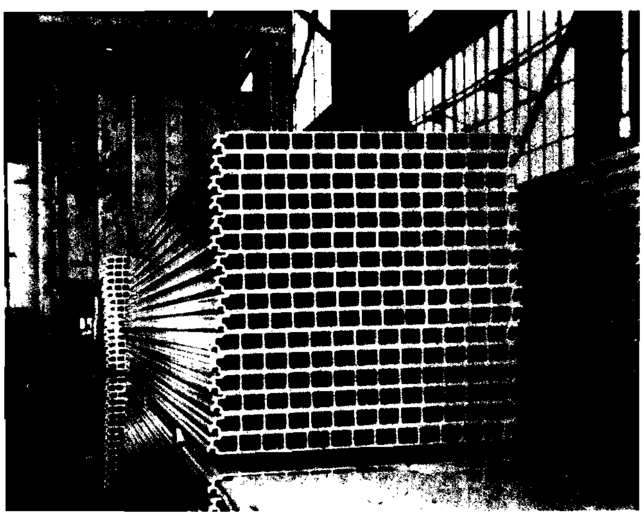


FIGURE 9. ALUMINUM ALLOY EXTRUDED LANDING-MAT SECTIONS USED IN WARTIME AIRFIELD CONSTRUCTION

High-Strength Materials

The development of Mach 2 and Mach 3 aircraft has produced a requirement that high-strength materials (higher strength than aluminum alloys) be used in the manufacture of these high-speed aircraft. This is the result of skin temperatures encountered in flight exceeding the temperature capabilities of aluminum alloys. Steel, of course, was a prime candidate but its weight penalties soon eliminated it from extensive usage. The development in the early 1950's of a basically titanium and steel SR71 high-altitude aircraft ushered in a new era necessitating the development of extrusion practices for titanium and titanium alloys[10]. The high-strength-to-density ratio obtainable with titanium at elevated temperatures made titanium the principal candidate construction material for these high-performance aircraft. As paralleled in the all-aluminum airplanes, the SR71 necessitated titanium in a wide variety of shapes. Some typical titanium alloy

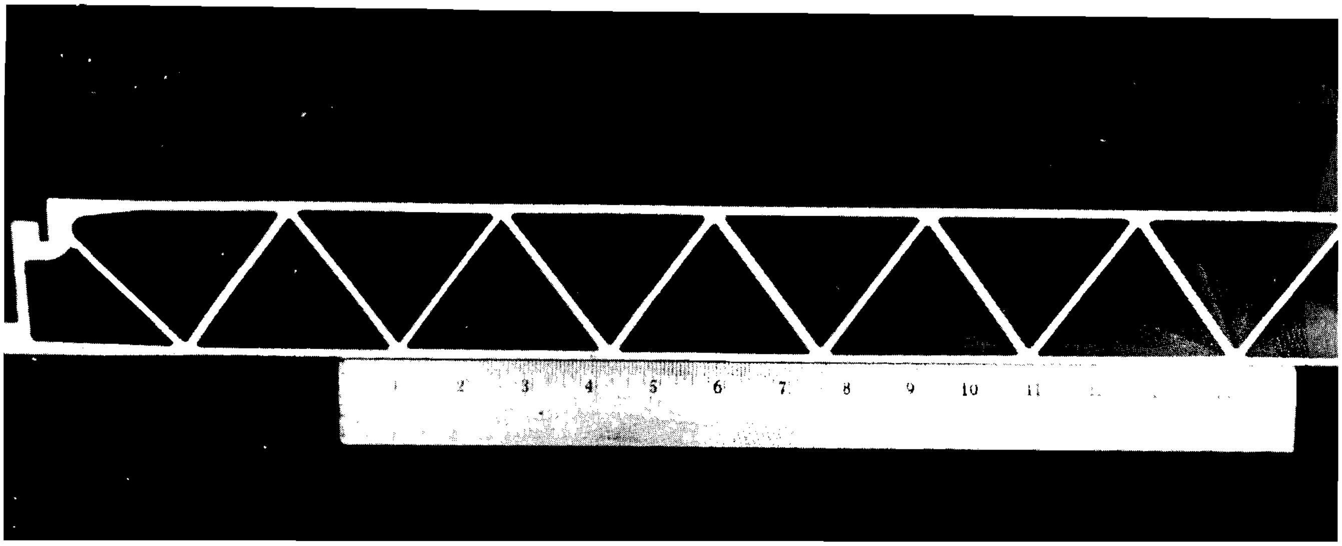


FIGURE 10. 10-FOOT-WIDE ASSEMBLY OF TRUSS-CORE EXTRUSIONS PRODUCED IN THE AIR FORCE 14,000-TON PRESS NOW OPERATED BY CONALCO, MADISON, ILLINOIS

As-extruded panel cross section is 24-1/2 x 3 inches.

extrusions shown in Figure 6 and Figure 11 show an integrally stiffened panel extruded from Ti-6Al-4V alloy in preliminary design studies aimed at the C5A aircraft construction.[11] While stiffened panels of this type have not been utilized in production, the manufacturing process is developed and available.

A distinctly different application for high-strength extruded shapes lies in the manufacture of aircraft jet engines. These extruded shapes are generally rolled and then welded into ring components and used, for example, in compressor case shrouds, as seen in Figure 12.

Extrusion is now deeply rooted as an important part of the manufacturing process for aircraft. Aluminum alloys, by virtue of the unlubricated extrusion techniques used in their manufacture, can be extruded to nominal dimensions and with as-extruded tolerances acceptable for aircraft construction. Necessity for much higher temperatures and for lubricated extrusion techniques for high-strength materials, requires high-strength extruded shapes be machined after extrusion prior to their utilization. As a result, alternative methods of manufacturing high-strength shaped components continue to be investigated, and a number of these have already found limited applications in aircraft. Some of these techniques are described and discussed in Section 4.

PRESENT COMMERCIAL EXTRUSION PRACTICES

In considering extrusion practices used for manufacturing structural shapes for aerospace applications, it is necessary to differentiate between those for aluminum and aluminum alloys (also magnesium alloys, although none are currently used in aircraft) and those for all other materials finding aircraft applications, such as titanium, steel, and other high-strength alloys. The basic differences between the two extrusion processes used are those of extrusion temperature, extrusion speed, and use of lubrication. High-strength aluminum alloys are extruded at temperatures on the order of 900 F, at exit speeds of 2 to 3 feet per minute, and the whole process is conducted without lubrication for billet or die. On the other hand, extrusion techniques for high-strength materials call for temperatures ranging from 1700 F to as high as 3700 F, exit speeds on the order of 10 feet per second, and elaborate lubrication techniques. In the following sections, the basic differences between the extrusion techniques are described in more detail and the process characteristics and extrusion conditions which are important in the successful extrusion of structural aircraft shapes are clarified.

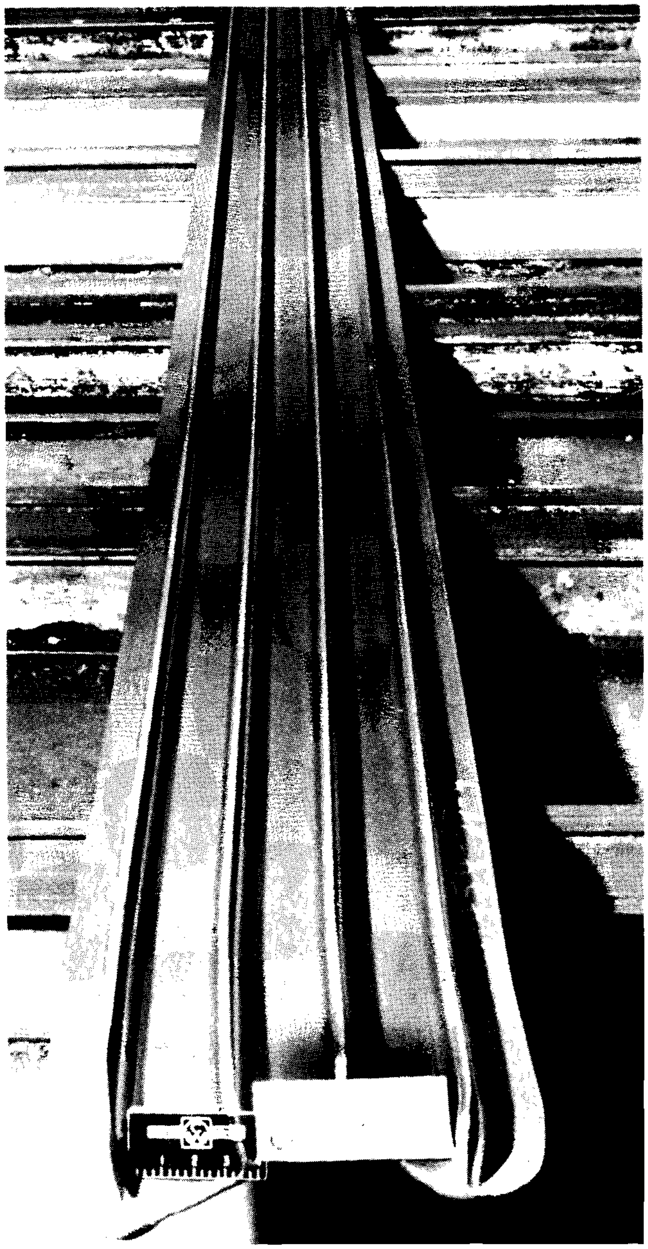


FIGURE 11. INTEGRALLY STIFFENED PANEL OF EXTRUDED Ti-6Al-4V[11]

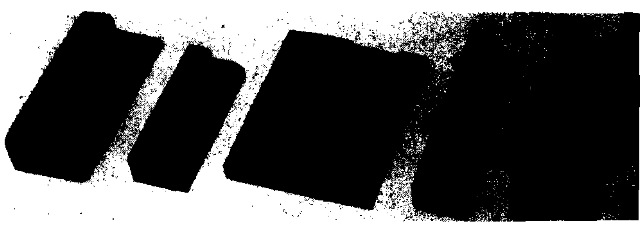


FIGURE 12. EXTRUDED TITANIUM SHAPES TO BE WELDED INTO ENGINE RING COMPONENTS[12]

ALUMINUM ALLOYS

Any discussion of fabrication techniques for aluminum alloys immediately reveals processing conditions interwoven with the metallurgical characteristics, grain size, and prior processing history of the alloy being extruded. The concern with these various factors is related to the desire to optimize physical and mechanical properties in the part after the final fabrication step. Consideration of these factors in the extrusion operation is extremely important.

While a variety of aluminum alloys are extruded and find applications, generally the 2000 and 7000 series alloys are the most widely used for aircraft applications. These alloys are very high-strength materials and are heat-treatable to strength levels on the order of 70,000 psi yield strength.

Aluminum extrusion is a good example of the basic extrusion process as it entails preheating the billet to the appropriate temperature, inserting it in an extrusion press against the die face, and exerting the necessary force on the back of the billet to start extrusion through the die. With aluminum, lubrication is not used and the entire operation appears rather straightforward and routine once conditions are defined. Hidden in this apparent simplicity is a vast number of interactive metallurgical and processing factors that can profoundly affect mechanical properties, surface finish, and corrosion resistance of the final extruded shape.

As discussed later, this extrusion method which uses no lubrication between the billet, container, and die, has been able to produce very complex extrusions (see Figure 5) with "mirror" surface finish and close dimensional tolerances that are considered net extrusions — that is — used directly in the as-extruded form in aircraft construction.

With this extrusion technique, a flat-faced (shear-faced) die is utilized. As pressure is applied to the end of the billet, internal shearing occurs across planes within the billet and fresh, unoxidized metal is forced through the die orifice. This fresh metal accounts for the bright finish obtained on an aluminum extruded shape. With this technique, however, very high extrusion forces are required because large amounts of redundant work result from the uneven flow pattern within the billet. This redundant work represents energy that is converted into heat and results in a gradual raising of the average billet temperature. If not controlled, this adiabatic heating can be sufficient to cause hot shortness and melting in the extruding material.

Since it is obviously desirable to achieve as high an extrusion ratio as possible, the maximum possible billet preheat temperatures are utilized. This combination of high extrusion ratio, high starting billet temperature, and the danger of overheating due to redundant work, necessitates very low extrusion speeds if a sound product is to be produced. Thus, a ram speed of 1/2 inch per minute is quite common, and, with a typical extrusion ratio of 40:1, exit speeds of the extrusion can be on the order of 2 to 4 feet per minute. Figure 13 shows a plot of flow stress versus extrusion speed for several aluminum alloys[13]. Note that 7075 and 2024 alloys are extruded at low rates and over a narrow speed range.

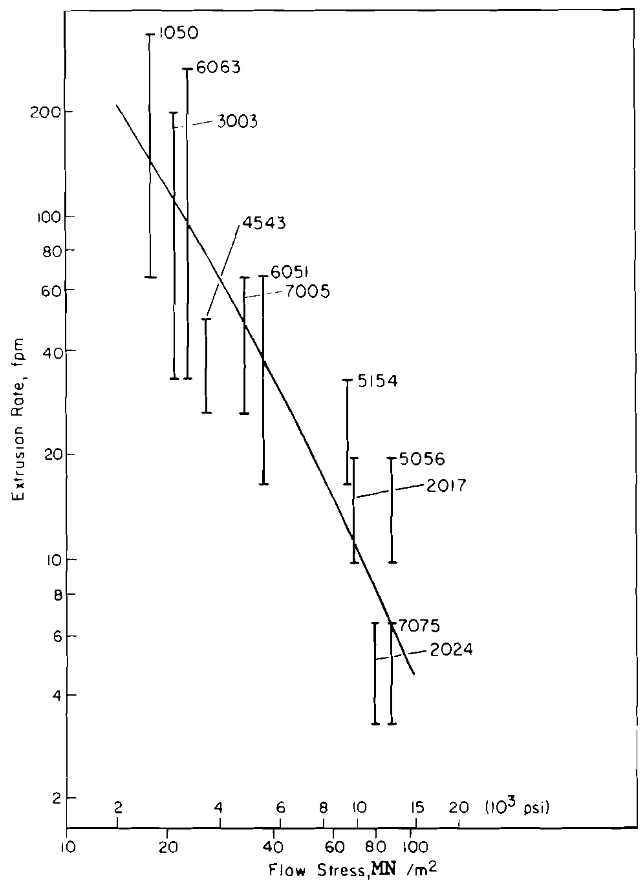


FIGURE 13. RELATIONSHIP OF EXTRUSION RATE AND FLOW STRESS FOR VARIOUS ALUMINUM ALLOYS[13]

To accommodate these low extrusion speeds, it is obvious that tooling temperatures must be maintained close to that of the billet so that chilling is minimized and does not become of sufficient magnitude to complicate the extrusion operation during the long extrusion cycle. On the other hand, since adiabatic heating can cause the billet temperature to rise, preheating techniques have utilized graduated heating in some facilities where the back of the billet is heated to a lower temperature. It is assumed that adiabatic heating during extrusion will raise the temperature of the last material extruded to the desired level. Also in recent years, computer controlled systems have been developed to vary the extrusion speed during the extrusion cycle to facilitate control of process variables and provide an extruded product of desired uniform quality.

The ability to control temperatures of billet and tooling at the same level and allow extrusion to take place at low speeds has at least one inherent advantage. Stepped extrusions can be made in which the cross-sectional area of the extruding piece can be increased during a single extrusion stroke. Figure 14 shows a stepped extrusion produced by stopping the extrusion stroke and modifying the die opening to increase the extrusion ratio. While dead metal zones in the transition area can cause difficulties in this kind of product, careful control of process conditions allows stepped extrusions to be made routinely. Generally speaking, the cross sectional area change does not exceed 5:1.

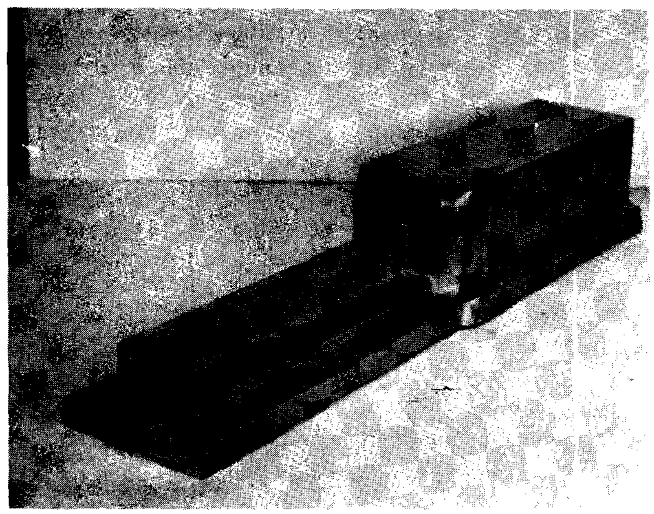


FIGURE 14. STEPPED ALUMINUM ALLOY EXTRUSION USED IN AIRCRAFT MANUFACTURE

An inherent feature in the aluminum-extrusion process, in which material is internally sheared against itself, can be utilized in the manufacture of thin-wall tubing and shapes that incorporate tubular type openings. This type of product is extruded through a bridge or port-hole die. This die design, shown in Figure 15, features port-hole openings in the top face of the die from which material is extruded into two or more segments, and then, beneath the surface of the die, welded and forced through the final shape configuration to form a part. The tubular portion of the extruded shape is formed

by a mandrel attached to the underside of the top die segment. This provides a fixed support for the mandrel and accommodates the provision of a continuous hole in the extruded part. Figure 16 shows several rather complex parts that can be made only through the use of a port-hole-type arrangement.

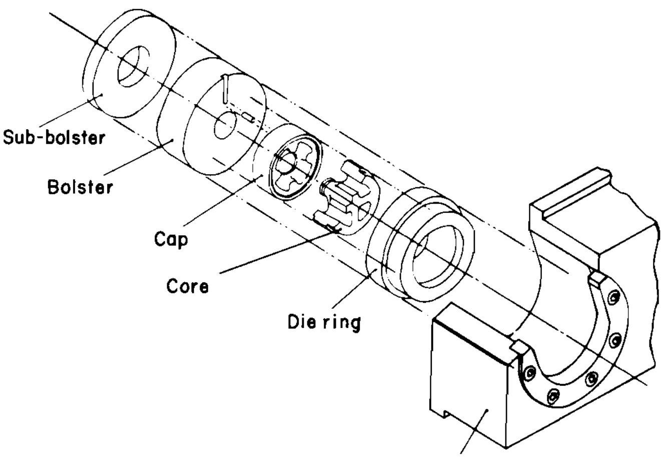


FIGURE 15. TYPICAL TOOLING ASSEMBLY FOR PORT-HOLE DIE EXTRUSION OF ALUMINUM ALLOYS[14]

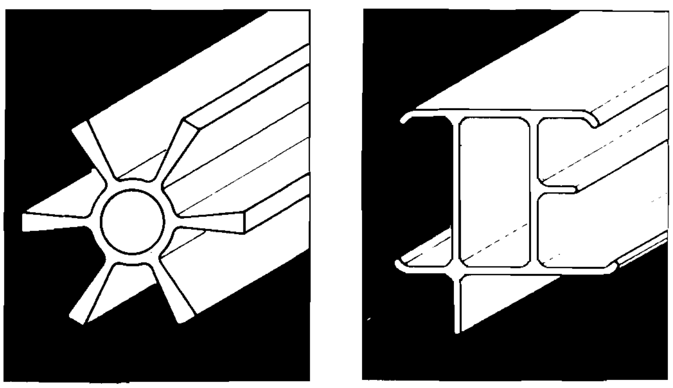


FIGURE 16. TYPICAL PARTS EXTRUDED THROUGH PORT-HOLE DIE

Billet Heating

Since only cast billet stock is used as extrusion billet material, it is imperative that the grain size and metallurgical structure of the casting be properly established so that subsequent working will yield a product of desirable properties and acceptable surface finish. Considerable efforts have been directed over the years to develop homogenization techniques to refine cast grain size and control the dispersion of insoluble phases in the proper form and size. An important part of the homogenization process is final cooling of the billet. If the billets are quenched too rapidly, alloying elements remain dissolved in solid solution and render the material more resistant to hot working. On the other hand, extremely slow cooling can result in the formation of large second-phase precipitates which enhance the material's workability, but adversely affect surface finish of the extrusion. This is one example in which metallurgical factors must be carefully controlled in the early stages of the total extrusion process even before the extrusion operation ever takes place.

Following homogenization of the billet, it is common practice to machine or scalp the outside diameter of the billet in order to remove impurities remaining from the casting surface. This technique is used primarily with the high-strength aluminum alloys that must meet stringent aircraft requirements.

It is also important that the metallurgical structure developed in the homogenization process not be destroyed by subsequent preheating the billet for extrusion. Thus, in certain alloys it is imperative that preheating of the billet to the proper extrusion temperature be done as rapidly as possible. This is best achieved through the utilization of low-frequency induction heating techniques. This care in preheating applies only to selected alloys, and many alloys can be batch-heated in gas fired furnaces without any problems.

Selection of the extrusion temperature depends on a number of major factors including complexity of the extrusion shape, extrusion ratio, available tonnage of the press, and the specifications and property requirements desired in the product. Higher temperatures lower pressure requirements but can adversely affect the surface finish. Conversely, lower temperatures improve surface finish but require higher extrusion pressures. In any event, the combined effects influence product quality and product properties, and the optimization of extrusion temperature requires careful control of all process conditions.

Die Design

A recent review by Huffman[3] has generally summarized the current status of tooling technology for aluminum extrusion. The unique ability of the aluminum extrusion process to manufacture thin, complex shapes with sharp corner radii immediately poses problems in the design and fabrication of an extrusion die will have sufficient practical life. Such an extrusion die must withstand heat, prolonged stresses, thermal shock, and, of course, friction wear. In general, the 5 percent chromium

hot-worked tool steels (H-11, H-12, H-13) find most widespread use as extrusion die materials since they combine good toughness and strength with wear and heat resistance. Longer life tooling (such as backers, bolsters, and containers) is most frequently made from lower alloy steels such as AISI 4140 and 4340. As these tools still see high pressures but do not experience the extreme temperatures, somewhat lower strength materials can be used.

Attempts have been made over the years to improve tool life, and studies made of other die materials and nitriding or other surface treatments to improve wear resistance. In general, attempts to improve die life by using high-temperature strength materials such as maraging steel and superalloys have been unsuccessful for die applications because of their poor wear resistance. Casting of dies holds some promise, as Huffman indicates significant cost savings through reduced machining and finishing requirements. Also, cast dies appear to be more resistant to heat checking than comparable dies fabricated from the same alloy in the wrought condition. In addition, dies can be cast with the die opening configuration in place so that only finish machining of the orifice is required. With wrought dies, the die slot must be chemically or mechanically milled and surface ground to the proper dimensions. In some instances, harder inserts have been positioned in sharp-cornered dies to attempt to improve wear resistance in selected areas.

In general, however, today's die-manufacturing techniques do not vary greatly from those employed in the industry over the past 50 years. Considerable hand work must be done in the manufacture of a new die and even more hand grinding and polishing is required in attempting to recondition used dies in order to enhance their useful life. Thus, the "artistic" factor remains an important part of present die manufacture for extrusion of aluminum. A recent book by Bello(14) describes the techniques used in designing and modifying extrusion dies to optimize metal flow and assure good surface quality.

Tooling Modifications for the Manufacture of Panel Sections

The United States and other countries have long used wide, integrally stiffened panels and other sections such as shown in Figures 3 and 8 for aircraft applications. The extrusion of these hard-alloy wide panels from cylindrical billets requires very high extrusion ratios and hence high extrusion temperatures. Even so, it is common practice in extruding these alloys to apply pressure to the billet for perhaps as long as 20 minutes before material begins to move, breakthrough occurs, and the extrusion movement begins.

One method of reducing this extrusion ratio is through the use of a rectangular billet. A rectangular container must also be used, but the advantages incurred are those of greatly reducing the press requirements for manufacture of wide panels. As an example, panel sections extruded from a round billet on a 14,000-ton hydraulic press can be manufactured on an 8000-ton press when a rectangular billet is extruded.

Rectangular containers are known to be in use in the U.S., at Alcoa, Dow, and Fruehauf Trailer Company for manufacturing truck-trailer bodies. In Europe, the Aluminum Walzwerk Singen GmbH in Singen, Germany, has a rectangular extrusion container for fabricating wide panels. With this type of nonsymmetrical tooling, it is imperative to utilize special care in the container design, manufacture, and operation. However, rectangular tooling operates satisfactorily, and designs for this type of tooling are available.(15)

Another approach to manufacturing wide panels has been to incorporate a piggy-back container between the container and die. This container has a tapered bore and allows a cylindrical billet, of for example 24-inch diameter, to be extruded through the system to fabricate a panel over 30 inches in diameter. With this technique, Kaiser Aluminum(16) (and others over the years) have extruded wide-panel sections for aircraft manufacture.

Indirect-extrusion techniques, which have been explored many times in years past, are finding some favor in recent times in attempts to reduce extrusion pressure requirements and improve grain-size uniformity in the extruded product. With indirect extrusion, the billet remains fixed in relationship to the container, and a hollow ram forces the die against one end of the billet. The extrusion billet is maintained by a stationary counteracting force applied by the main ram that normally provides the extrusion force for a direct-extrusion operation. This technique results in significant reductions in breakthrough pressure requirements, and can significantly increase throughput by virtue of the reduced dwell times before breakthrough occurs.

This reduced pressure requirement results primarily from eliminating the billet-container friction which exists in a direct-extrusion operation in which the billet surface must move in relationship to a stationary container liner. A second improvement reportedly achieved through the use of indirect extrusion involves large grain size formation on the surface of the extruded shapes. Studies have shown that, in some alloys, the surface layers on the outer periphery of an extruding section are chilled sufficiently below the hot working temperature to cause a recrystallized surface grain on the extruded surface. Work in this area reported by Bennett(17) and others indicates

that tensile properties, hardness and fatigue strength of extruded shapes can be affected adversely by the presence of such a surface layer. Figure 17 shows the variation in grain structure from surface to center of an extrusion as evidenced in etched fatigue specimens. Some reports indicate that this condition can be alleviated somewhat by the use of indirect extrusion techniques.

FIGURE 17. VARIATION IN GRAIN STRUCTURE ACROSS EXTRUDED ALUMINUM ALLOY SHAPE AFTER -T4 HEAT TREATMENT[17]

Left, fine grained -T4 specimen; center, inside a surface specimen; right, coarse grain at outside of extrusion.

Postextrusion Processing

An important area of any aluminum extrusion plant contains postextrusion processing equipment to transform the extruded shape into a straight, distortion-free product of desired metallurgical uniformity, surface finish, and mechanical properties. Depending upon the alloys, air quenching or water quenching off the press is followed by subsequent heat treating and/or aging to obtain the desired properties. All extruded shapes are stretch-straightened and detwisted and they frequently go through some roller straightening or even gag straightening after final heat treating and sectioning to achieve the desired distortion-free dimensions. It has been estimated that approximately 30 percent of the total cost of manufacturing an extruded shape lies in the processing steps that are required after the extrusion step is completed. This high percentage suggests that some new and different techniques are needed for the extrusion of aluminum alloys in order to reduce these high costs of postextrusion processing.

Use of Speed-Control Systems

In view of the desirability to carefully control extrusion speed and reduce chances of overheating during the extrusion cycle, several investigations have studied approaches to provide a more accurate control of extrusion speed than is possible with a strictly manual operation. An article by Haverkamp[18] discusses extrusion-press speed-control systems. Those systems widely used in foreign countries program desired extrusion speeds for various portions of the cycle, and utilize computer-operated controls to enable these conditions to be repeatable.

The most desirable way of controlling the overall extrusion cycle would be to monitor exit extrusion temperature and utilize this information through a feedback system to control the extrusion speed. Attempts in this direction have been limited principally in developing a reliable temperature-measuring device. Reynolds[19] and Beattie[20] of British Aluminum Company have reported development of a radiation pyrometer which apparently worked quite satisfactorily in aluminum extrusion. Present information does not indicate whether this system is functioning on a production basis.

Undoubtedly, efforts along these lines will continue as there is much to be gained by automating an aluminum extrusion set-up. Of course, the primary advantage such a system offers is manufacturing large quantities of a single extruded shape. With many aircraft alloys, however, while tonnages are quite high, the number of extrusions made is not sufficient to justify attempts to utilize fully automated speed-control systems. However, present-day extruded shape requirements dictate carefully controlled process conditions and it is common practice to extrude at speeds less than the maximum desired in order to provide some allowance for sudden changes in temperature of the process conditions. Thus, it is highly desirable to continue development of process-control systems in order to increase material throughput and reduce scrap losses off the extrusion press.

EXTRUSION OF HIGH-STRENGTH MATERIALS

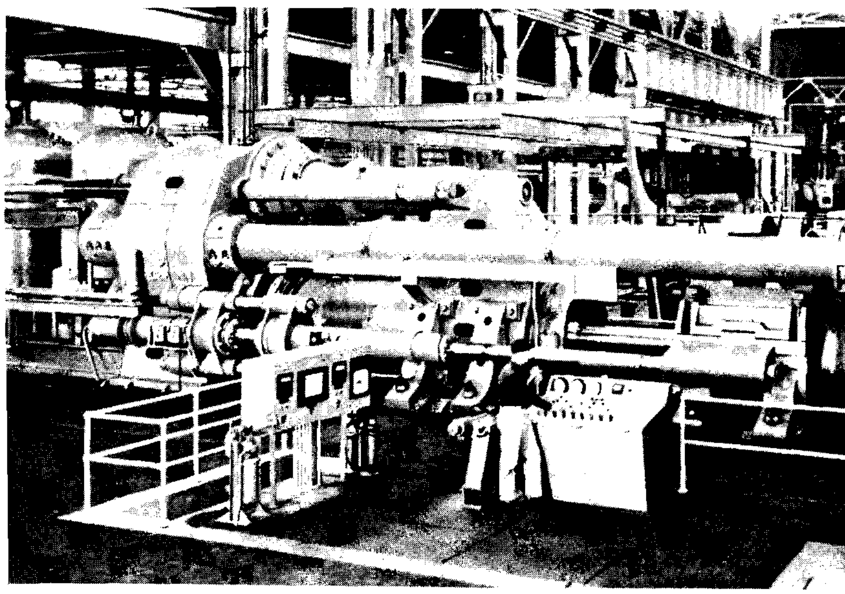
As indicated earlier, development of the glass-lubrication process in the 1940's provided the key to the ultimate success in production extruding structural shapes in long lengths as well as tubing and solid shapes. The role of glass as a lubricant is discussed in more detail in a subsequent section. However, the unique features of glass as a lubricant are its ability to soften selectively during contact with the hot billet, and, at the same time, to

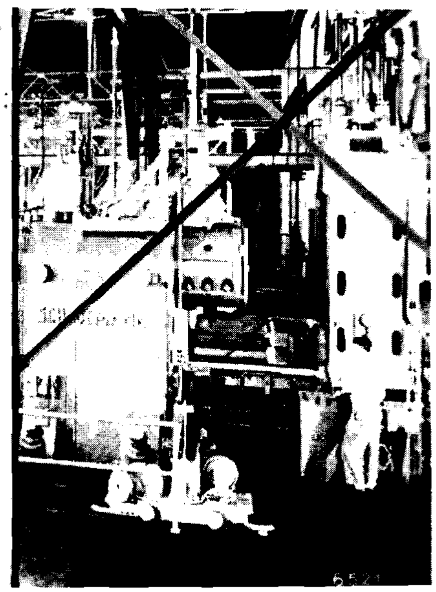
insulate the hot billet material from the tooling which must be maintained at a considerably lower temperature.

With high-strength materials, extrusion is generally at a minimum of 1800 F and can go as high as 3500 to 3700 F for some very high-strength materials. It is apparent that problems can occur at these high temperatures when it is recognized that the maximum temperatures which tooling can tolerate are essentially the same as in the extrusion of aluminum, namely a maximum of about 900 to 1000 F. As a result, tool life is always a major factor in establishing acceptable process conditions and defining process costs. While less than ideal in many cases, the only way to obtain compatability between the very hot billet and considerably cooler tooling is to use appropriate glass lubricants, insulative die coatings and ceramic die inserts, and to design dies to minimize tool wear as much as possible. Some work has been done in water cooling dies to increase tool life, but this technique has not found widespread use. To date, only glass has worked on a production basis in extruding long lengths, and much technology has been developed over the years in the use of glass.

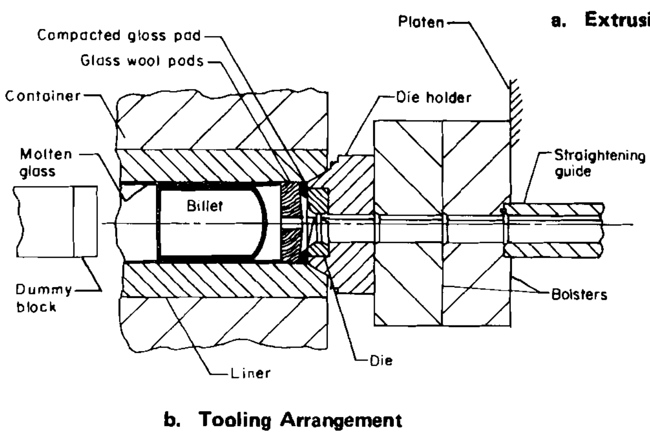
Figure 18a shows a typical hot-extrusion press and Figure 18b shows a typical tooling arrangement utilized in a high-speed hot-extrusion press, where the various components come together and remain together for the few seconds that is required to accomplish a single extrusion cycle.

The general procedures used in high-temperature extrusion consist of heating the properly prepared extrusion billet to the hot extrusion temperature. The billet may be heated in an induction heater, a gas-fired or electrically resistance heated furnace, or a combination thereof. Once at the proper temperature, the billet is quickly transported to the press and, most commonly, rolled over a bed of ground glass or sprinkled with glass powder which supplies a layer of low melting glass to the billet surface. Prior to insertion of the billet into the hot extrusion container, a suitable die glass lubricating system is positioned immediately ahead of the die (this may consist of a compacted glass pad, glass wool, or both). The prelubricated billet is quickly inserted in the container followed by appropriate followers or a dummy block and the exertion of force on the end of the stem starts the extrusion cycle.





a. Extrusion Press



b. Tooling Arrangement

FIGURE 18. HOT EXTRUSION SETUP USING GLASS LUBRICATION

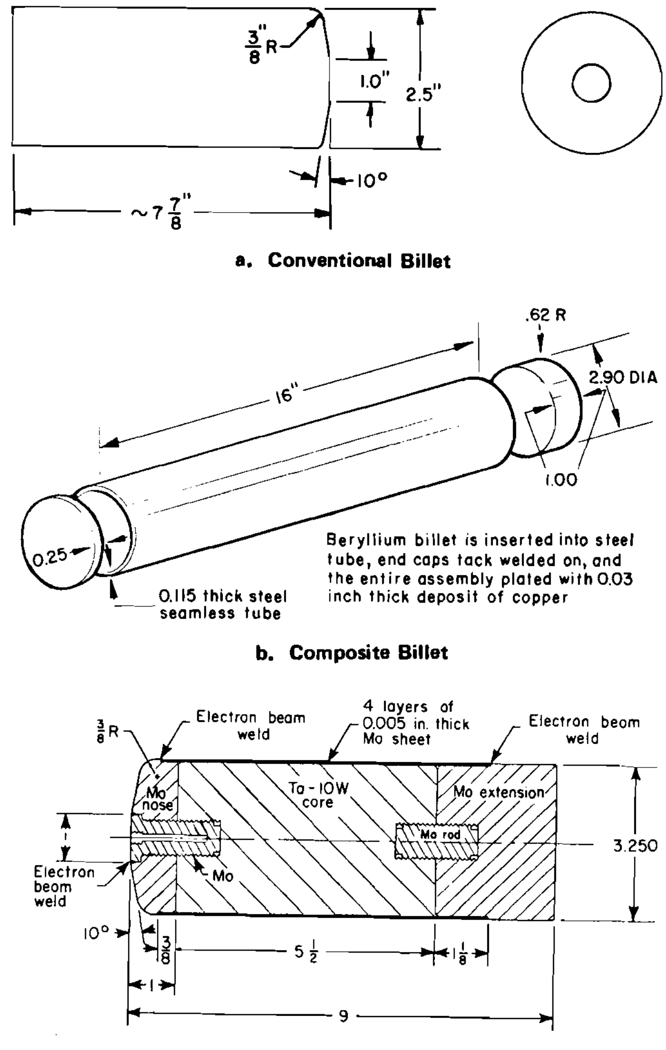
Once extrusion is completed, tooling is separated, the residual butt separated from the die, and the tools cleaned and reconditioned in preparation for the next cycle. Subsequent portions of this section center around the components in the extrusion operation and characteristics and features that make each necessary to the successful use of the process.

Billet Preparation

General practice in extruding most high-temperature materials utilizes forged or rolled materials as starting billet stock. In keeping with the aircraft requirements on properties and impurity levels, most materials used extensively are cast by multiple, consumable-electrode arc-melting operations with a minimum requirement that one of the melting steps be in vacuum. Subsequent forging or rolling of this product insures that a more uniform starting material will be available as billet stock.

Cast billets of some refractory materials have been pre-extruded inasmuch as the cast material is generally of low ductility and coarse grain size and is not readily adaptable to upset forging or rolling. Also, coarse grains in these instances would ultimately be reflected in the nonuniform residual grain size which can show up in the extruded part. In extruding powder metals, the powder may be compacted in a separate can fabricated from wrought stock. These powders may be partially densified in a separate operation or put in the canning stock and compacted in the can before typical steps of evacuation and sealing of the end. For some very difficult-to-work materials, composite materials have been assembled to overcome specific processing problems encountered when a given material is extruded alone.

Figure 19 shows three billet designs which are examples of the types discussed above. Figure 19a shows a conventional extrusion billet such as would be utilized with steel or titanium, Figure 19b a composite billet design in which the beryllium billet is inserted in a seamless steel tube, and Figure 19c a complex billet configuration utilized for extruding Ta-10W material. Here molybdenum stock is placed at both the nose and aft ends of the billet and a molybdenum sleeve encases the billet surface. Such a complex billet design is aimed at preventing contamination of the tantalum billet which is extremely susceptible to oxidation at elevated temperatures.



a. Conventional Billet

b. Composite Billet

c. Clad and Molybdenum Wrapped Billet

FIGURE 19. EXAMPLES OF BILLET DESIGN USED IN HOT EXTRUSION OF HIGH-TEMPERATURE MATERIALS

In any lubricated extrusion process, the surface of the billet becomes the surface of the extrusion. This means that often special care must be taken in preparation of the OD surface of the billet since it can affect surface quality on the extrusion. Extrusion billets are always machined on the OD surface and are typically finished to a 30 to 60 microinch, CLA, finish. Some billets, particularly those for titanium, may be further grit-polished with 100 grit paper to provide a smoother surface finish. Billet surfaces may also be centerless ground to insure good extruded surfaces. As is shown in Figure 19a, a chamfer or radius on the nose of the billet facilitates starting uniform flow through the die opening at the outset of the extrusion. Typically, these areas are machined and finished identical to the OD surface of the billet.

Heating high-temperature materials represents one of the most costly and most important steps in the entire extrusion procedure. Since these materials have high strengths, they must be heated to quite high temperatures in order to reduce the flow stress and to achieve high extrusion ratios. Care must be exercised to prevent billet contamination during heating. This problem is especially aggravated with materials that are highly susceptible to oxidation.

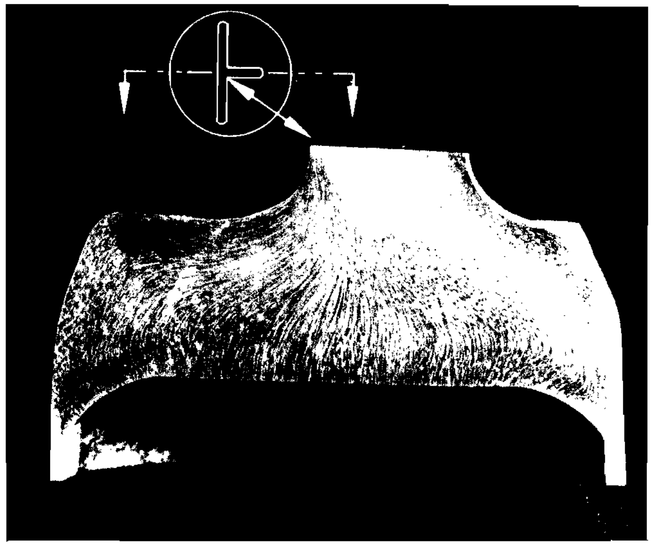
Various techniques have been utilized to protect billet surfaces during heating. Salt baths have been successful in some instances although they are not particularly adaptable to high production operation. A resistance-heated furnace with an argon atmosphere also works quite satisfactorily but it also is limited from a high production rate standpoint.

A common practice is to degrease the billet surface and precoat it with a high-temperature protective glass slurry prior to heating the billet either in air or protective atmosphere. This method provides the needed protective coating and is adaptable to a production environment. In recent studies by North American (now Rockwell International)[21] a glass bath was used as a heating medium quite successfully in preventing contamination of the billet surface during heating.

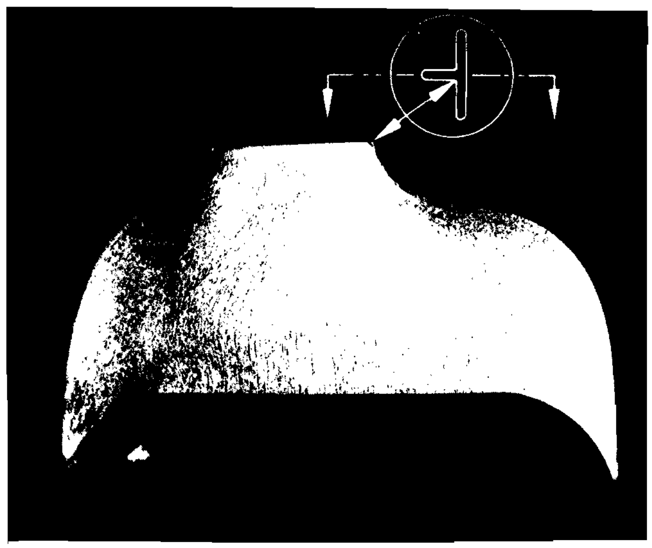
The technique most adaptable to a production set-up is the combination of precoating with a glass slurry followed by low-frequency induction heating. The induction heating may be done under a nitrogen atmosphere. This technique is flexible and rapid and allows a high power efficiency. Heating may be done in a two-stage operation. After preheating to some intermediate temperature the billet is heated quickly to the extrusion temperature just prior to its insertion into the extrusion press. It is important to note the use of a glass precoat on the billet requires careful cleaning and degreasing of the billet prior to applying the glass coating. Otherwise, problems in adherence of the coating to the surface can be anticipated.

Die Designs and Die Material

The key to the development of a set of reproducible extrusion parameters for extruding a given shape is highly dependent upon the ability to develop a suitable die design and select a proper die material. Appropriate conditions will enable high-quality extrusions to be made on a reproducible basis. Since the die is subjected to high pressures and high temperatures, it is imperative that material flow through the die be optimized in order to prolong die life. Material flow through a die depends on die entry design and the contour formed by the die and the glass-lubricant pad positioned between the hot billet and die. The importance of the die lubricant is shown in Figure 20. Figure 20a shows extrusion without a die glass pad. While no "dead metal" zone occurs, material flow is not uniform. Figure 20b shows the uniform metal flow obtained when the die-lubricant reservoir is of the proper weight and configuration for the die design. By optimizing metal flow, extrusion pressures can be minimized and die life extended. While no "dead metal" zone is shown in Figure 20, such zones occur in practice if insufficient glass is present on the die. This is evidenced by a metal ring left in the container after extrusion.



a. Extruded Without Glass Pad



b. Extruded With Glass Pad

FIGURE 20. STEEL BUTT CROSS SECTIONS SHOWING EFFECT ON METAL FLOW OF USING A GLASS PAD ON THE EXTRUSION DIE[22]

Note Smoother Flow in (b).

Figure 21, a simple extrusion die for a T-section, shows the variations used in die-face contour to promote uniform metal flow through the die in conjunction with a glass pad. The general die design shown is typical of those used in most production-type operations for simple shapes. Obviously, variations in the die design depend on the specific shape being extruded.

FIGURE 21. THREE-PIECE DIE CONSTRUCTION USED FOR HOT EXTRUSION OF TEE SHAPES

Conventional hot work tool steels such as AISI Type H-11, H-13, and H-21 are used for most commercial extrusion operations when the extrusion temperature does not exceed about 2200 F. When temperatures are higher and long lengths are required, it is desirable to use either ceramic coatings on the tool steel die face or ceramic inserts for the dies. Coatings of zirconia and alumina are frequently flame sprayed on tool steel dies to provide added life. The role of the ceramic coating is simply to insulate the die from the heat of the billet. A typical coating procedure for applying a zirconia coating to a die is given below:

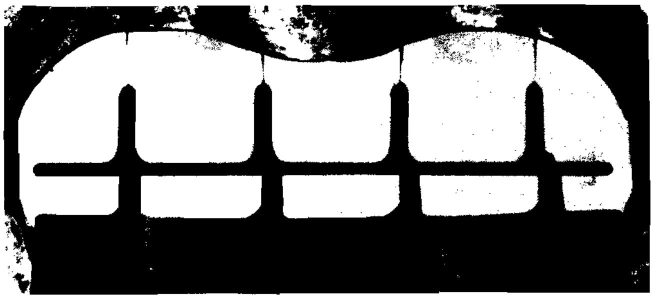
- Grit blast die surface
- Degrease with residual-free chemical such as methyl ethyl ketone
- Spray 0.003 inch layer of molybdenum on die surface (optional step)
- Plasma spray 0.015 inch layer of alumina or zirconia on die surface
- Grind and polish surface to leave 0.010 inch ceramic layer on die surface.

A three piece or segmented tool-steel die facilitates the use of the flame-spraying since this is the only technique available for getting the coating on the die land for thin-section extrusion. Of course, if the die opening is large enough, the die land of a one-piece die can be ceramic coated. Manufacturing segmented steel dies is costly and is not widely practiced in industry.

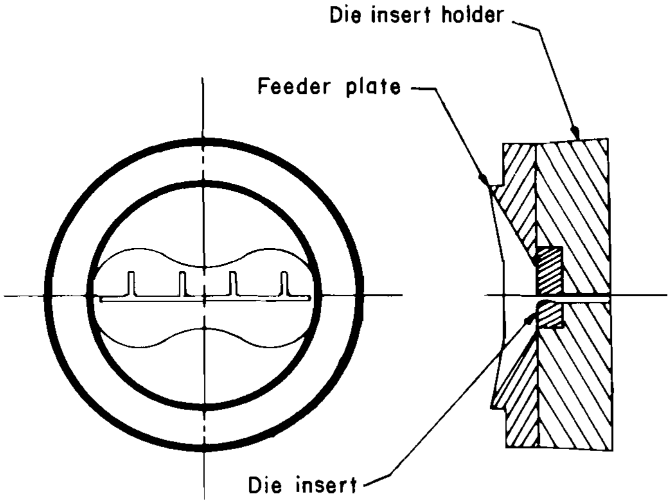
The other problem with the use of a flame-spray coating is that the coating is disturbed frequently when the extrusion cycle is completed and the extrusion must be pulled partly back through the die in order to separate the butt. It has been a general experience that the coating performed very satisfactorily during extrusion but was easily chipped off the die face upon retraction of the part. This, of course, necessitates recoating of the die between extrusion cycles.

It should be pointed out that the use of inserts becomes more common as extrusion temperatures go up, and also as extrusion shape complexity increases even when lower extrusion temperatures are used. Figure 22 shows an H-shaped die fabricated from four ceramic segments that were held together in a container ring and used for extruding molybdenum at temperatures on the order of 2500 F.[23] Figure 23a shows a 16-inch-wide ceramic die assembly which was used for extruding titanium alloys[11]. Figure 23b shows the overall configuration of the die with its conical flat design in which the die opening is in the flat of the die and a feeder ring serves as the conical entry portion of the die.

FIGURE 22. FOUR-PIECE H-SHAPED CERAMIC DIE AND CONTAINER RING USED FOR EXTRUDING MOLYBDENUM[23]



a. Die



b. Schematic

FIGURE 23. DIE ASSEMBLY FOR EXTRUDING TITANIUM ALLOY PANEL SECTION SHOWN IN FIGURE 11[11]

As indicated above, ceramic inserts are used when a shaped configuration is extremely complex or extrusion temperatures necessitate their use. Both alumina (Al_2O_3) and zirconia (ZrO_2), which are highly densified pressed and sintered materials, are used. Use of a ceramic insert necessitates both peripheral and base support of the die since ceramics have very little tensile strength and must be maintained in compression during use. A new product called "Cerrotherm"[24] reportedly has excellent life as a die-insert material in tests made with high-temperature materials.

It is evident from the schematic drawing of extrusion tooling and the various components in the hot-extrusion process (see Figure 18), that considerable die support is necessary in an extrusion setup particularly where complex or thin section shapes are to be extruded. Dies of this design are extremely susceptible to elastic movement under pressure and must be adequately supported if die cracking is to be prevented and if conditions to provide close control over extruded dimensions are to be maintained. Figure 24 shows a die and die-support system used for extruding a U-shaped beryllium section. The large die bolster required in contrast to the small die itself is evident in this photograph.

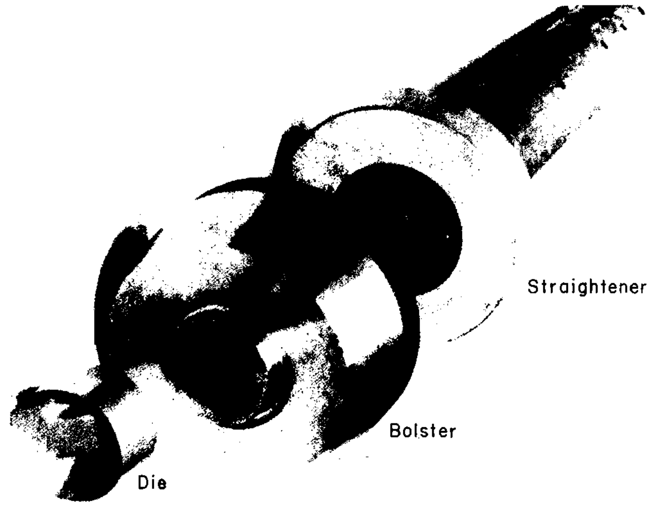


FIGURE 24. EXPLODED VIEW OF DIE, BOLSTER, AND STRAIGHTENER ARRANGED IN SEQUENCE FOR EXTRUSION OF BERYLLIUM U-SHAPE[25]

Also shown in Figure 24 is a straightener which was used at the exit end of the die bolster system to assist in maintaining straightness of the extruded shape as it emerged from the die. It is common occurrence that extrusions are severely twisted and distorted as they exit from the die. Normal practice calls for warm detwisting and straightening of hot extruded shapes after extrusion except for air-hardening steels which must be annealed before straightening. However, materials low in ductility have been straightened through the use of a graphite "straightener" or guide behind the die bolster to reduce straightening requirements after extrusion.

Lubrication

As indicated earlier in the historical discussion of the development of the hot extrusion process, the development of glasslike materials as lubricants holds the key to the ultimate success in extruding high-strength materials successfully and economically in long lengths. Optimum lubrication in such a system, where wide temperature gradients must be tolerated between the billet and the die, is a basic process parameter that must be properly established before any material or configuration can be extruded to representative commercial requirements for tolerance, surface finish, and so forth.

The definition of a glass has been given as "a liquid having virtually infinitely high viscosity which in heating

shows no sharp transition to the fluid state"[26]. This definition describes the first requirement of a hot extrusion lubricant, namely, that of exhibiting no sharp transition to the fluid state. The viscosity of glass and the change in viscosity with temperature play an important role in the success of this material as a lubricant. Figure 25 shows the effect of temperature on viscosity at atmospheric pressures. Since no good quantitative method is available for defining the viscosity required in extrusion, the behavior of glass at high temperatures *under high pressures* is not well understood. Attempts to assess the effects of pressure on viscosity[27,28] have generally concluded that pressure had no effect on viscosity. Thus, it has been largely on the basis of experimental trials and viscosity values measured at atmospheric pressures, that glass lubrication practices have been established for successful work in a production atmosphere.

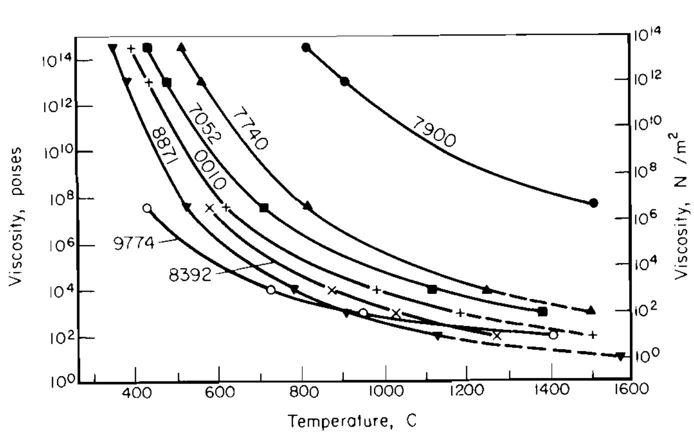


FIGURE 25. VISCOSITY OF GLASSES AS A FUNCTION OF TEMPERATURE

Data from Corning Glass Works, Corning, New York, U.S.A.

In addition to the viscosity, a second important property required of a hot-extrusion lubricant is thermal conductivity. One of the advantages of glass in the hot-extrusion process is its ability to insulate the cooler tooling from the hot billet during the few seconds that the two are in contact with each other. While this insulating effect must be maintained, enough heat must be transferred so that progressive layers of the glass lubricant soften and lubricate the extruding billet.

Reviews of the development of glass lubrication processes have been given by Sejournet[29] and also by Zagar and Schneider[30]. Initial work with ordinary window glass as a lubricant attempted to use glass discs cut from rolled window plate. This approach met with difficulty because the glass had poor thermal conductivity in this form and often cracked and split in small pieces when placed in contact with the preheated billet. It was not until later when developments by Babcock and Wilcox[31] using a particulate glass of appropriate mesh size and mixed with a binding agent to form the die glass pad, that a production process was successfully developed for extruding long lengths.

Glass lubrication basically incorporates a glass pad or glass wool or both positioned in the die ahead of the billet plus a glass film on the billet surface. The role of the die pad is to soften upon contact with the hot billet and progressively diminish in thickness as successive layers of glass soften to lubricate the extrusion billet as it passes into the die. This die pad does not lubricate the billet surface prior to its entry into the die. Container lubrication, which must be separate from that of the die pad, is accomplished by coating the heated billet with a lower viscosity glass. The preheated billet is rolled over a bed of glass particles of a composition selected to develop proper viscosity and lubricating characteristics along the container wall and to wet the billet surface. This container lubricant must retain adequate viscosity during the extrusion stroke when the hot billet is in contact with the much colder container liner wall.

In addition to selecting a die glass pad material, the thickness of the pad and its configuration must be considered. That is, whether the pad is to (1) be a simple cylindrical ring, (2) have a tapered surface in contact with the billet, or (3) have a sculptured ID contour as dictated by the die design and the shape to be extruded. If too much glass is used, the pad will crush at the start of extrusion and may plug the die opening, particularly with a shaped extrusion when a thin section is to be extruded. Plugging can also occur if the hole in the die pad is not large enough. Economically, it is desirable to use as little glass as possible; this tends to work in the right direction in terms of eliminating problems of die plugging caused by the presence of excess glass.

Another consideration in glass viscosity and pad configuration is possible reaction between the glass and the material to be extruded. Reactive materials such as titanium require special glass compositions that eliminate, or at least minimize, reactions between the glass and the metal that cause the formation of brittle oxides on the surface and subsequent deterioration of surface quality on the extruded part. Despite the short contact time between the glass and billet, the combination of temperatures and pressures can combine to cause severe reactions between the glass the billet.

It should be evident from this short discussion that the formulation of a successful hot extrusion glass lubricant system requires considerable experience and expertise. Basic patents for this process are the property of CEFILAC*, and currently over 30 companies around the

*Formerly Compagnie du Filage des Metaux Curty, Paris, France.

world utilize what is known as the "Sejournet glass extrusion process" under license from CEFILAC. These patents represent developments by CEFILAC as well as by companies who have participated in the licensing arrangement with CEFILAC over the years. These developments have helped expand and develop the glass lubricated extrusion process.

In general, specific glass compositions used in industry are considered proprietary. The literature indicates some typical glass compositions that have been used for high-temperature lubrication. Table 1 shows some examples of lubricating glasses.[32] Table 2 shows chemical compositions of some Soviet lubricating glasses in conjunction with Figure 26 which shows how viscosity of these glasses changes with temperature.[33] Higher viscosity glasses contain high percentages of silica with aluminum, calcium, sodium, potassium, and boron oxides added in varying amounts to control the viscosity at a given temperature. The discussion of the glass lubrication process must also include a third glass form which is frequently encountered in the extrusion operation. It is common practice in some operations to position a small pad of low-density glass wool (such as that used in house insulation) ahead of the die pad. The composition of this glass wool will vary depending upon the extrusion temperature being utilized. Its role is to provide a small amount of glass that will soften very rapidly upon contact with the hot billet. This helps lubrication get started while the first layers of particulate glass in the die pad are beginning to soften and flow. The quantity, form, and composition of this glass wool pad is another factor to be optimized for a given extrusion process. Also, this glass wool must be free of carbon binders which form CO and CO_2 and cause surface defects on the extruded shape.

TABLE 1. EXAMPLES OF EXTRUSION LUBRICATING GLASSES[32]

Type	Fibre Glass	23H Tissue	"E" Glass	Pyrex Glass	Window Glass	Neutral Glass
Soda (Na_2O)	14.5	13.0	--	3.8	14.5	8.7
Silica (SiO_2)	65.0	65.0	54.0	80.5	74.0	67.0
Borax (B_2O_3)	--	6.0	10.0	12.9	--	7.5
Iron (Fe_2O_2)	--	--	--	--	--	--
Lime (CaO)	11.0	7.5	17.0	--	10.0	4.0
Magnesia (MgO)	7.5	4.5	4.5	--	--	0.3
Alumina (Al_2O_3)	2.0	3.0	14.5	2.2	1.0	8.6
Zinc Oxide (ZnO)	--	1.0	--	--	--	--
Tin Oxide (SnO)	--	--	--	--	--	--
Titanium Oxide (TiO)	--	--	--	--	--	--
Potash (K_2O)	--	--	--	0.4	--	4.0
Softening Point	710 C	750 C	850 C	--	700 C	--
Fluid Point	1120 C	1095 C	1350 C	--	940 C	--

TABLE 2. CHEMICAL COMPOSITION OF USSR LUBRICATING GLASSES[33]

Glass	Chemical Composition, percent						
	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	B_2O_3	Other Oxides
1	56	15	18	2		7	2
2	65	3	10	15			7
3	50		15	19	5	3	8
4	56	2	15	20	3	2	2
5	60	3	15	15		3	4

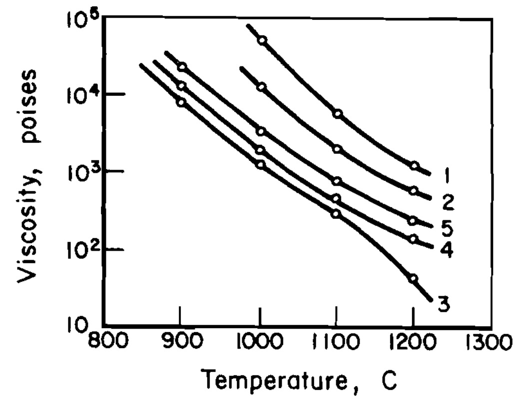


FIGURE 26. TEMPERATURE AND VISCOSITY RELATIONSHIPS FOR GLASSES IN TABLE 2[33]

The discussion of the types and forms of lubricants used in hot extrusion suggests complications in adapting the techniques to a production environment. However, once the conditions have been optimized, reproducible extrusions can be produced at typical production rates of 60 to 80 billets per hour. Production rates of 120 billets per hour can be achieved – despite the fact that a new glass pad and glass wool compact, if used, must be positioned on the die face prior to each extrusion stroke.

Efforts have continued over the years to find replacements for glass lubricants. Studies at TRW[34] explored many materials as potential lubricants. Of the extensive catalog of lubricant materials developed, several showed attractive lubricating characteristics at elevated

temperatures and were successfully demonstrated in the extrusion of high-temperature materials. However, the limitation here, as for all other nonglass lubricants developed to date, is the inability to maintain a good lubrication and insulating s'stem in the extrusion of long lengths. A number of compounds on the market surpass the performance of conventional grease-graphite lubricants in hot extrusion or forging of relatively short lengths. Some are too expensive to use routinely. For example, a patent of Streicher[35] and assigned to DuPont has demonstrated the success of a metal oxalate in combination with graphite and a hydrocarbon lubricating oil in extruding 5-foot lengths of zircaloy tubing at temperatures of 1000 F. With this material, a 3-foot-long titanium alloy tube extruded at 1700 F showed excellent surface finish. While these and other lubrication systems have been developed and used at temperatures approaching those now used in hot extrusion, glass lubrication currently remains unchallenged for use at temperatures above about 1800 F as a production method for hot extrusion.

Postextrusion Processing

Generally the first steps involved in processing an extruded product after extrusion are the straightening and detwisting normally required for shaped type products. Tubular products are processed through roll straighteners. For many high-strength materials, cold straightening can be very difficult and special tooling is required to induction heat the piece to some elevated temperature so that deformation sufficient to cause straightening can be applied. If the extrusion product is to be heat treated, it is normal practice to straighten and detwist the shape before heat treatment. Additional straightening may be required after heat treatment to remove the distortion frequently encountered during heat treatment.

Beyond this step, postextrusion processing involves removal of the glass film remaining on the extruded surface. This may be accomplished by several means. Some extruded shapes are water-quenched immediately off the press to thermal shock the glass film and break it loose from the extrusion surface. Others are pickled in appropriate acid solutions to dissolve the glass. The pickling technique is particularly needed for tubular products where spray quenching off the press cannot be utilized on the ID surfaces. Straightening also removes some residual glass.

As indicated elsewhere, present hot-extrusion techniques for high-strength materials do not produce extruded shapes that meet aircraft and aerospace requirements in the as-extruded condition. Extensive efforts over the years have been directed toward utilizing both cold and warm drawing techniques to produce "net dimension" shapes that require no further finishing. Details of these processing techniques are described in Section 3. These techniques have not proven economical, particularly in view of the limited production quantities now common in the aircraft industry. Currently, extruded shapes purchased for aircraft usage are machined on all surfaces to achieve the desired dimensional tolerances and remove any residual surface oxidation products developed during the hot extrusion operation. With highly reactive materials such as titanium alloys, contamination is particularly critical and sufficient material must be removed from the surface to insure contaminant-free surfaces.

Critical Extrusion Parameters

For the extrusion of a given shape, if die design, lubrication, and other process parameters are reasonably well-established, the pressure required to accomplish extrusion is the function of the extrusion ratio and a constant, C, which incorporates a variety of influencing factors that are discussed in more detail below. In its simplest form, the equation is one $P = C \times$ naperian logarithm of R (extrusion ratio) where,

P = extrusion pressure

C = constant

$$R = \frac{\text{cross sectional area of billet}}{\text{cross sectional area of extrusion}}$$

Many, more complex equations have been developed to better accommodate the various factors affecting extrusion pressure. Here, it is sufficient to consider this simple equation and to examine the various factors, and their interrelationships. If the constant, C, is known and well-established for a given set of extrusion conditions, then it is quite simple to insert a desired extrusion ratio in the equation and determine what pressure would be required to accomplish extrusion. Experience shows, however, that the constant, C, is closely tied to a given set of extrusion conditions and is often difficult to accurately define – hence the efforts to develop more involved equations for calculating pressure requirements.

The most common practice for determining the constant, C, is to extrude a given material and product shape at different extrusion ratios and different temperatures and measure the extrusion pressure. In this manner then, the value for the constant, C, is most frequently determined. It is generally assumed that this constant decreases in a linearly fashion with increases in extrusion temperature.

It is interesting to examine briefly the various factors that are interrelated to make up the constant, C. The foremost factor is the resistance to deformation of the material, or flow stress, at the temperature selected for extrusion. This flow stress, however, is affected not only by temperature but increases with strain rate — a factor that can become significant at high strains and high temperatures. Thus, while flow stress can be expected to drop as temperatures rise, the effect may be offset by strain-rate effects at high temperatures. It is conceivable then that even when the temperature rises, strain-rate effects can effectively increase flow stress, or at least negate the normal effects of temperature.

A second factor in the constant is the coefficient of friction. Values of 0.01 to 0.02 are frequently quoted as the friction coefficient in extrusion using a glass lubricant. Some pressure equations include a component which utilizes the friction coefficient values indicated above. Also affecting the constant, C, is a shape complexity factor. For a given extrusion ratio and extrusion temperature, it is reasonable to expect pressures to become higher as shape complexity increases. This effect may result from increased friction or lower extruding temperature due to chilling by the greater surface area of the die, or both.

Ram speed and extrusion speed, of course, are reflected in consideration of the strain-rate effects mentioned earlier. Extrusion speeds are, of course, quite important to the process since high speeds can cause breakdown of lubrication, material melting, or hot shortness in the extruded material. Slow speeds allow billet chilling to occur and pressure requirements immediately rise.

Typical ram speeds of 2 to 6 inches per second are most commonly utilized. It is obviously highly desirable to extrude as rapidly as possible not only from a production rate standpoint, but also to limit contact time between the high-temperature billet and the much cooler tooling in the press.

With titanium alloys, for example, ram speed is critical and is normally controlled between 4 and 6 inches per second. Lower speeds cause chilling of the billet and breakdown of lubrication; higher speeds can result in abnormal billet heat-up and problems with die wash and lubrication.

Limitations also exist in the tooling pressure that can be accommodated and in the hot-working ranges

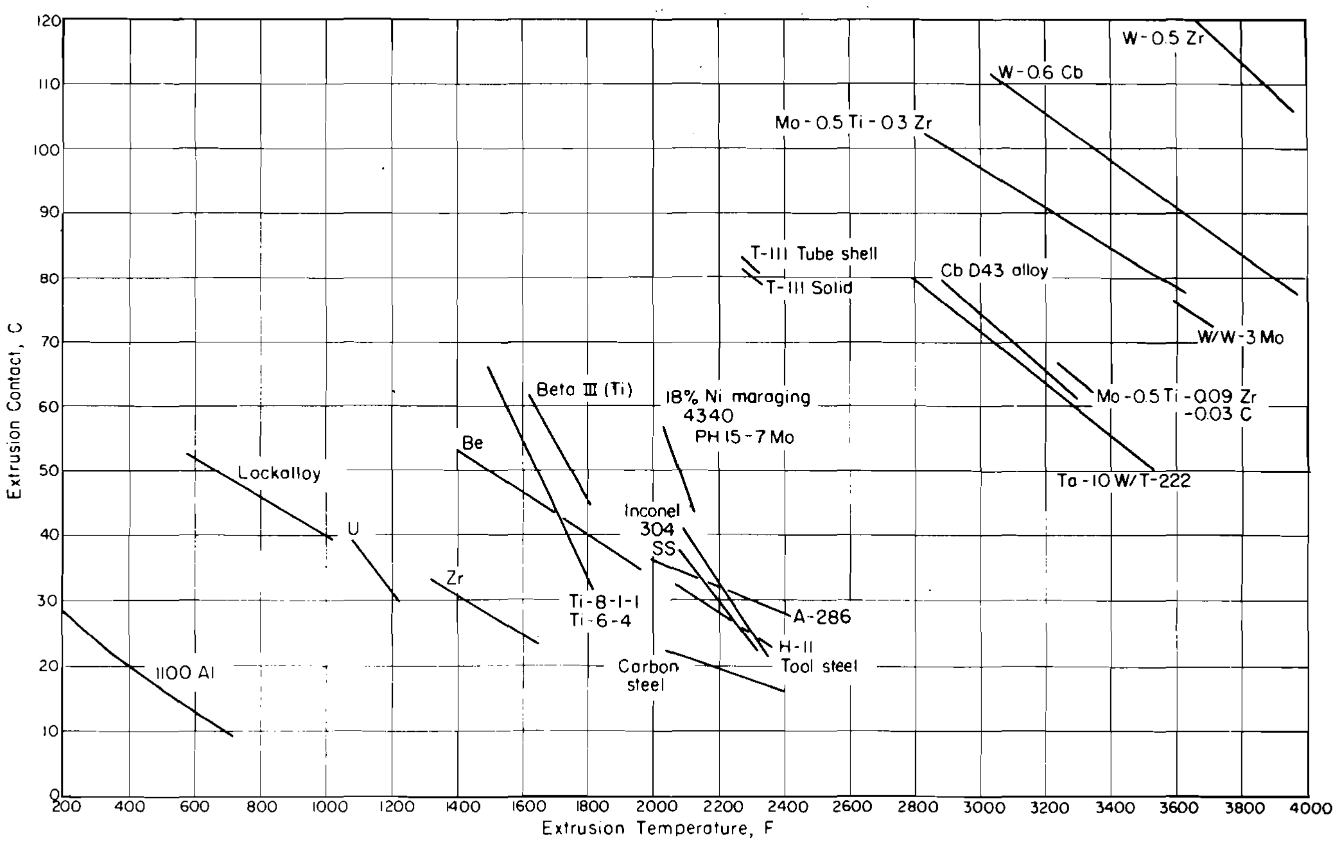


FIGURE 27. EXTRUSION CONSTANTS FOR A VARIETY OF MATERIALS

permissible for various materials. These two factors in themselves directly affect the obtainable extrusion ratio. Usually, stem pressures of 180,000 psi are considered to be the upper limit beyond which press or tooling damage can occur. However, Santoli[36] has developed a tooling system which will operate at 300,000 psi pressure. Routinely, however, stem pressures of 125,000 to 150,000 psi are considered normal. To maintain these high pressures, water accumulator systems are used on extrusion presses for extruding these alloys in contrast to simple oil pumps used on aluminum-extrusion presses.

If calculations show that extrusion pressures are too high then two factors can be changed – the extrusion ratio can be reduced, or the billet temperature raised so as to lower the constant, C. However, all materials have limited hot working ranges that can be affected by problems in hot shortness, melting of secondary phases, or production of highly undesirable large grain sizes in extruded products. Therefore, practical limitations of hot-working ranges and pressure limitations of extrusion presses can significantly affect the maximum extrusion ratios that can be achieved.

Figure 27 shows a plot of extrusion constants versus temperature for a wide variety of materials. This plot contains data reported in the open literature as well as those calculated on the basis of pressure and extrusion ratio data from Battelle work and various Government reports.

EXTRUSION OF TITANIUM ALLOYS

The first application of titanium in an aircraft occurred in 1948 when a total of 535 pounds was used in the fabrication of a Douglas DC-3 airplane. Since that beginning, more time and effort has been spent on developing titanium alloys for aircraft manufacture than all other materials, excluding aluminum, combined. The basic reason for this intense interest is that titanium has about the same strength as higher grade steels, but it is over 40 percent lighter. This strength-to-density advantage, shown graphically in Figure 28, points up the potential for this material in high-performance aircraft and aerospace applications. This advantage exists not only at room temperature but, more importantly, at elevated temperatures where high-speed and high-performance aircraft must have operational capabilities.

The first major experimental program aimed at establishing the feasibility of hot extruding titanium structural sections for aircraft was begun in 1951 at Lockheed Aircraft Corporation under Air Force contract.[10] In this study, both rounds and structural shapes were extruded,

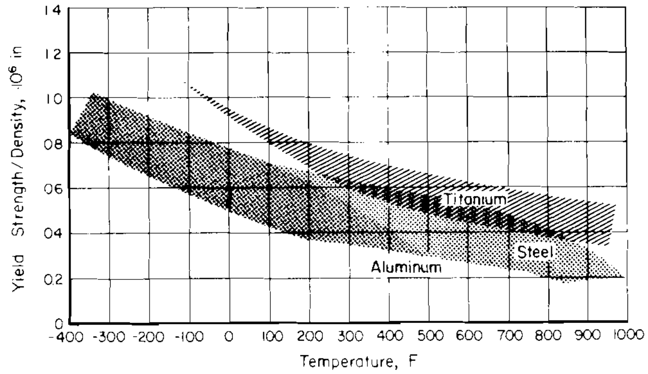


FIGURE 28. COMPARISON OF STRENGTH-TO-WEIGHT RATIOS FOR TITANIUM, STEEL, AND ALUMINUM

and this work established the feasibility of extruding structural shapes. (It was not, however, until some 15 years later that the probable basis for this rather extensive initial effort came to light when President Lyndon Johnson announced that the United States had a high-altitude supersonic speed aircraft, the SR-71, which was fabricated primarily from titanium alloys and steel and utilized extensive quantities of titanium alloy structural shapes.)

This initial program by companies employing the Sejournet glass extrusion process in the extruding of commercial steel products indicated that (1) titanium alloys could be extruded into structural shapes and (2) many complex technical problems had to be overcome if structural shapes were to be producible with dimensional tolerances and surface finishes comparable to those obtainable in aluminum alloys. Following the initial Lockheed work, Air Force-sponsored studies were carried out primarily under contract to Fairchild Hiller Corporation, Republic Aviation Division[37] although several companies were developing their own technology for producing titanium shapes. More recent Air Force-sponsored programs in the area of titanium extrusion have been conducted by Nuclear Metals Incorporated[6].

The quite-extensive Republic program established many basic extrusion processing techniques used today in producing titanium shapes. This work indicated that the practical limits on extruded thickness (particularly for the Ti-6Al-4V alloy) was about 0.09 to 0.1 inch. Since 0.04 to 0.06-inch section thicknesses were desired, additional efforts were undertaken to warm and cold draw these extrusions to thinner cross sections and to improve dimensional conditions, straightness, and twist. Improved techniques that were developed fell short of matching conditions obtainable in aluminum.

Subsequent programs included the extrusion of wide panels of potential use in the Lockheed C-5 aircraft designed and built in the 1960's. As shown in Figure 11,

this program was quite successful in fabricating an integrally stiffened panel using the 12,000-ton extrusion press at the Curtiss-Wright Corporation.[11] With the de-emphasis on high-performance aircraft manufacture in the mid- and late 1960's, developmental efforts on titanium alloys were reduced materially. Today, only limited manufacturing studies are under way. One involves the extrusion of Beta III alloy at Nuclear Metals Incorporated.[6]

Since the first trials in the 1950's, technology for extruding titanium has advanced in terms of billet heating practices, lubricant compositions, die materials, die designs, and general handling procedures. Even with present techniques, titanium extrusions cannot be produced economically to net dimensions, and overall surface machining is required to meet aircraft requirements. Even so, the technology developed in these manufacturing programs over the past 20 years has advanced the state of the art in hot-extrusion practices for titanium alloys and all other high-temperature materials as well.

The extruded titanium alloy shapes shown in Figures 6 and 12 are typical of airframe structural shapes readily extrudable with present hot-extrusion practices. Figure 29 shows some additional shapes extruded by Cameron Iron Works.

Extrusion of Titanium and Titanium Alloy Tubing

While seamless tubing is commercially available only in commercially pure (CP) titanium, some experimental quantities of Ti-3Al-2.5V alloy are being produced for evaluation in aircraft applications. Although considerable work has been devoted to defining extrusion practices and tube-reducing procedures for manufacturing Ti-6Al-4V alloy tubing[38], this alloy is not available as a seamless tubular product. A new alloy, Ti-3Al-8V-6Cr-4Mo-4Zr, that has been developed on a program conducted by Reactive Metals[39] could be available commercially in tubular form in the near future.

The general procedure for extruding titanium or titanium alloy tubing consists of canning a drilled tube billet in copper, heating the copper clad billet to a temperature of about 1500 F, and extruding it at a ratio of about 12:1 to produce a tube shell. The copper cladding is removed and the tube shell is processed by tube reducing and/or drawing to small-diameter tubing.

The complex alloy developed by Reactive Metals represents a sharp contrast in terms of formability as

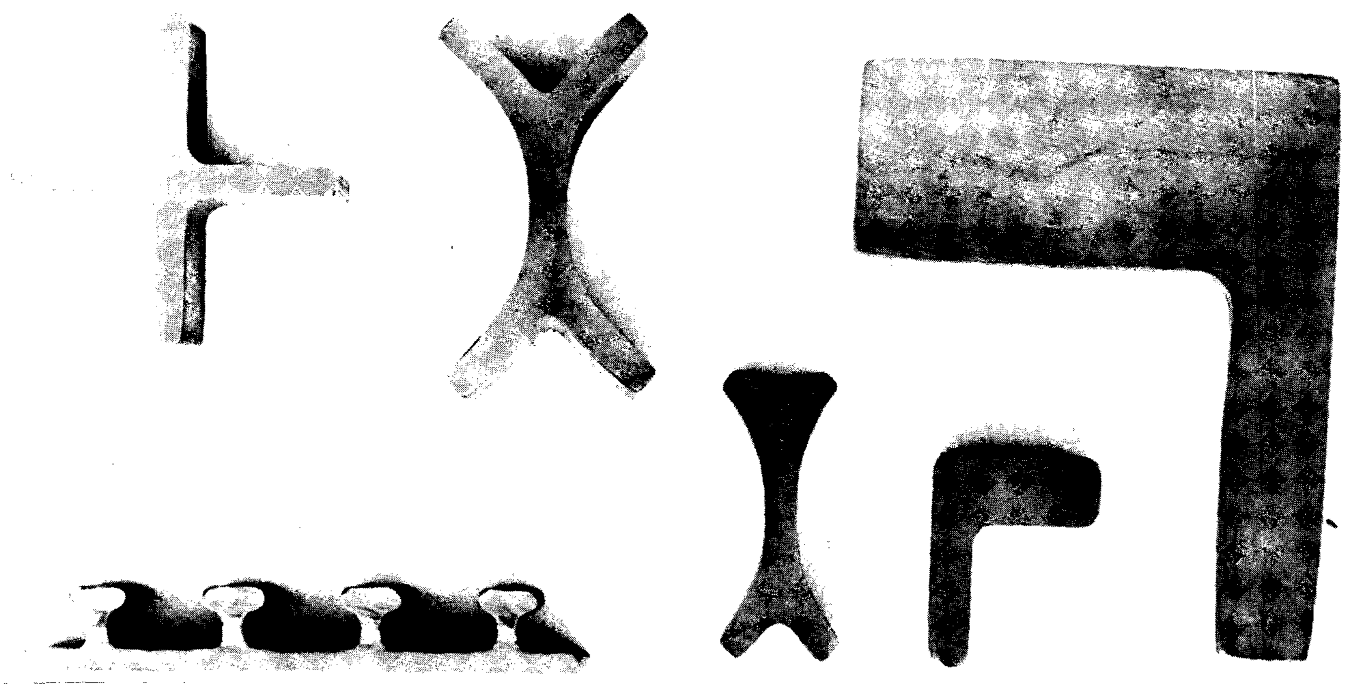


FIGURE 29. TYPICAL LARGE TITANIUM EXTRUSIONS BY CAMERON IRON WORKS

Photo Courtesy Cameron Iron Works, Houston, Texas

compared to other alloys that have been available in tubular form. Figure 30 shows a sample of 0.540-OD x 0.030-inch-wall tubing bent a number of times successfully without the cracking or rupturing problems which have long plagued attempts to produce tubing from other titanium alloys.

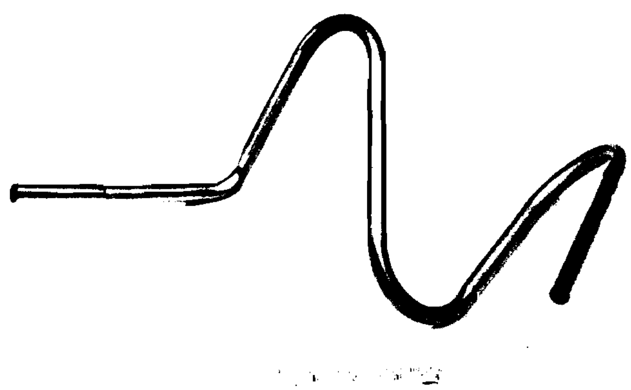


FIGURE 30. BENT SAMPLE OF Ti-3Al-8V-6Cr-4Mo-4Zr SEAMLESS TUBING[39]

Tube size 0.54 inch OD x 0.03 inch wall.

Processing Conditions Used

Table 3 contains typical extrusion conditions for extruding a variety of titanium alloy shapes.

EXTRUSION OF STEEL

Steel was first extruded in the late 1920's in experiments in both France and Germany. The work was in collaboration with steel manufacturers and fabricators of nonferrous metal products such as copper and brass. The theory was that if copper could be extruded at elevated temperatures, then the same should be true of steel.

These early experiments showed that while steel could be extruded, tool life was too short for extrusion to be an economical process under the same conditions used for copper. New higher temperature tool steels were needed for tooling along with techniques for preventing scale formation during heating. Also needed were higher press ram speeds than were obtainable with copper extrusion presses, plus a suitable lubricant to reduce friction and prevent extruding material from sticking to the tools.

Development of high temperature extrusion practices continued in the 1930's in England as related by Graham.[32] What is now the Henry Wiggin and Company, Limited, plant in Glasgow, Scotland, developed extrusion techniques for nickel, nickel-copper, some nickel-chrome alloys, and stainless steel in both tubing and some shapes. This early work led to Inconel tube billets being shipped from Inco in the United States to Glasgow for extrusion and return early in World War II.

The major breakthrough in the development of an economical extrusion technique for steel came in the late 1930's and early 1940's when Mr. Jacques Sejournet was attempting to extrude steel on a 600-ton extrusion press which had been used for brass, copper, and aluminum extrusion. He met the same problems mentioned above during these trials and it was not until late 1940 and early 1941 when efforts aimed at developing an extrusion lubricant which was neither solid or liquid at the working temperature was developed. These workers began with a mixture of borates and phosphates, and eventually came to the conclusion that ordinary glass was the solution to their problem. On November 22, 1941, Jacques Sejournet and Louis Labataille filed a patent covering the ideas of using glass-like materials as an extrusion lubricant. This patent, of course, subsequently issued along with a long series of improvement patents, and the Sejournet glass extrusion process is now well-known the world over and widely practiced by over 30 companies in 12 countries under licensing arrangement with CEFILAC for the extrusion of all types of high-strength materials.

The weight of steel has been a major deterrent to its extensive use in aircraft construction. Where very high load-carrying capability is required (such as for the fuselage wing carrythrough structure, wing-flap components, landing-gear hydraulic-cylinder tubing), steel extrusions are used. This is in addition to use of extrusions as rolled-and-welded rings in jet-engine manufacture.

As for titanium alloys, the first major program in the U.S. involving steel extrusion was an Air Force-sponsored program in the early 1950's.[10] In the work at Lockheed Aircraft Corporation, an AISI Type 410 stainless steel was extruded along with 4130, 4630, and 4340 alloy steels. A cruciform shape and T- and H-sections that were extruded demonstrated the extrudability of steel, defined basic extrusion parameters, and showed the effect of extrusion on material properties. Following this program, Lockheed, of course, proceeded in the design and construction of the then classified SR-71 aircraft which utilized rather large quantities of steel extrusions. However, extrusion practices were not without problems, and section thicknesses of approximately 3/16 inch were extruded and supplied to the aircraft manufacturer for subsequent allover machining to achieve the thin (0.060 inch) cross sections desired.

TABLE 3. GENERAL PROCESSING DATA FOR EXTRUSION OF TITANIUM AND TITANIUM ALLOYS

BILLET PROCESSING

Starting Stock

Forged or rolled material from multiple consumable-electrode melted stock with one melting step having been done in vacuum. Cast ingot should be reduced approximately 80 percent for elimination of cast grain structure.

Machining

Billets cut, ends faced parallel, and OD machined and ground to 6 microinch, CLA, finish. Nose end may be chamfered 10 to 15 degrees with ~0.4 inch corner radius or flat with radius alone.

Precoating for Heating

(1) Wash with soap and water
(2) Rinse with ketone degreaser
(3) Heat to 250 F to dry surface
(4) Spray or dip 0.010-inch coating of No. 85 glass

Heating for Extrusion

(1) Electric muffle furnace heating with billet enclosed in canister and surrounded by argon, or
(2) Low-frequency induction heating followed by 3 to 5-minute soak at maximum temperature, or
(3) Molten-glass bath

Typical Extrusion Temperatures

Metal	Shapes	Rounds/Tube Shells
CP Ti		
Ti-3Al-2.5V		
Ti-6Al-4V	1800 F	
Ti-6Al-6V-2Sn		1500 F
Ti-8Al-1Mo-1V	1850 F	
Beta III	1850 to 1900 F	

EXTRUSION CONDITIONS

Lubrication

Container glass	100 mesh 318-100
Die glass	3KB-14
Glass wool	
Necroline coating in liner	

Tooling Temperature

Container	900 F
Die	900 F

Ram Speed

Typical	Ti-6Al-4V	Beta III
2.5 to 3.7 ips	4.2 ips	2.7 to 4.0 ips

Tooling Materials

Container liner – T-1 high-speed; 48 R_c; 0.008 to 0.010-inch chromium plate
Dies – H-21 tool steel; 49 to 52 R_c; spray coated with 0.003 inch molybdenum followed by 0.016 inch zirconia – finish grind surface layer to 0.010-inch thickness
Die bolsters – H-11 tool steel, 44 to 48 R_c

POSTEXTRUSION PROCESSING

Deglass (or descale)

(1) Immerse the cooled extrusion (400 F) in a molten sodium hydroxide/sodium hydride bath at 860 F for 2 to 3 minutes
(2) Rinse in cold water
(3) Neutralize in 22 percent sulfuric acid bath for 1 minute
(4) Rinse thoroughly in cold water

Remove Surface Oxides

(1) Pickle in a 6 percent HNO_3/1 percent HF/water bath at 130 F
(2) Thoroughly rinse extrusion in cold water

Hot Detwist and Stretch Straighten

(1) Attach extrusion to insulated jaws of a 150-ton detwisting and straightening press having two 1000-ampere rectifiers as a dc resistance heat source
(2) Impose 550 amperes on the extrusion, apply some tension, and heat for 3 to 4 minutes
(3) When extrusion is between 1100 and 1200 F, start stretching
(4) After stretching 2 to 3 percent, turn off power
(5) Cool – gradually release pressure during cooling
(6) Remove straightened extrusion after cooling to 300 F to 400 F

Descale and Pickle – as described previously

With the design and subsequent construction of the B-70 aircraft, a second program involving steel extrusion was undertaken in 1958 and continued over a period of 10 years with Northrup Corporation, Norair Division, as the prime contractor.[22,40] During this time, extrusion trials were conducted in plants of most major U.S. extruders and some trials were conducted by CEFILAC. These efforts were aimed at establishing manufacturing methods for thin section steel shapes. Alloys extruded in the course of this program were: Type H-11 grade tool steel (5 percent chromium hot-work steel), A286 alloy, AISI 4340, PH14-8 Mo, 18 percent nickel maraging steel, and PH15-7 alloy. In the course of these studies, extrusion parameters were defined for fabricating 0.063-inch thick structural shapes from the alloys listed.

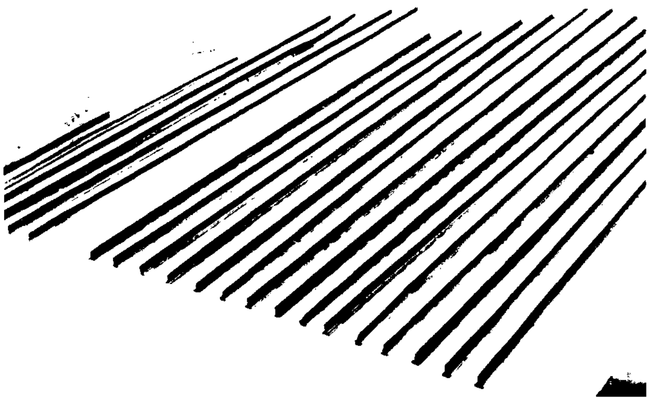


FIGURE 31. EXTRUDED H-11 TOOL STEEL AND AISI 4340 STEEL TEE SHAPES

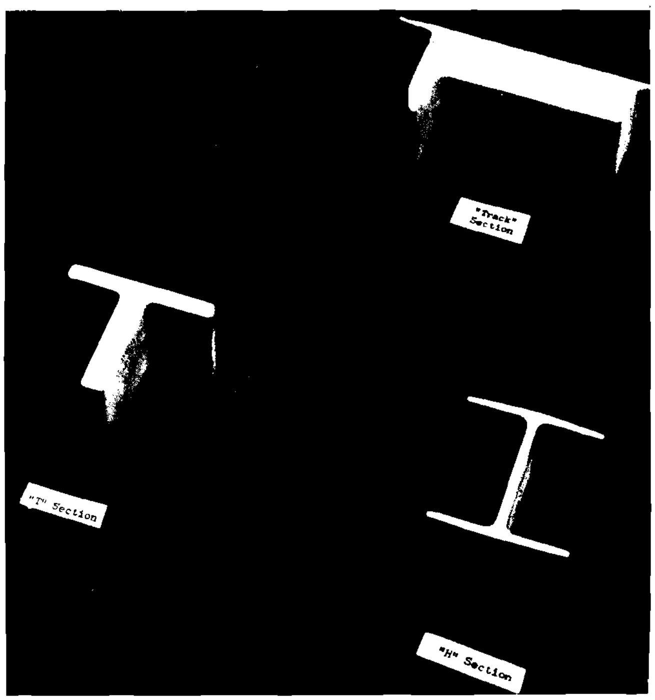


FIGURE 32. EXTRUDED STEEL SHAPES PRODUCED IN THE EARLY 1950'S AT THE START OF AIR FORCE-SPONSORED MANUFACTURING DEVELOPMENT PROGRAMS[10]

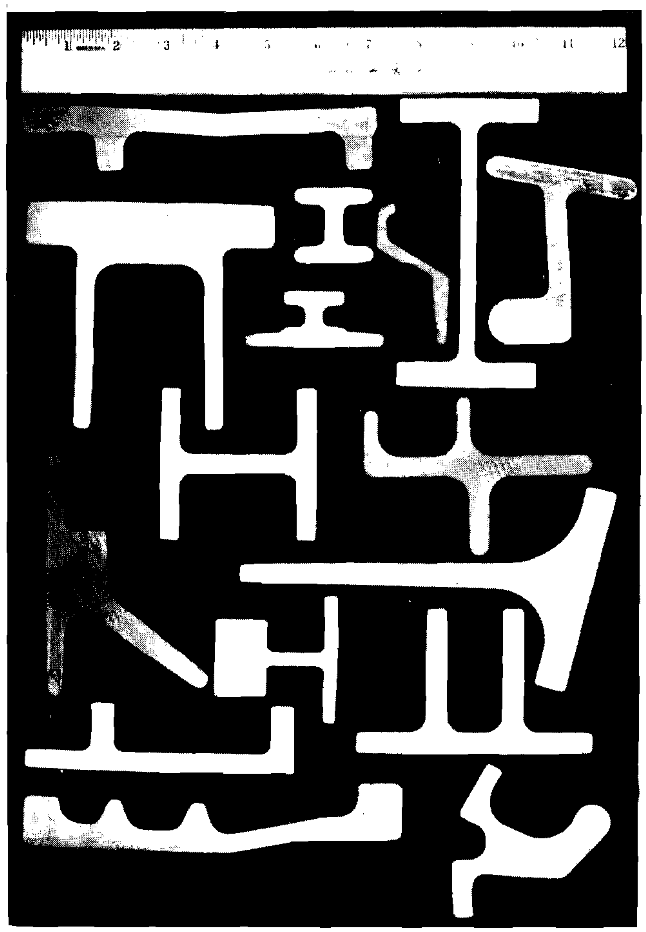


FIGURE 33. TYPICAL STAINLESS STEEL EXTRUDED SHAPES

Photo Courtesy Martin-Marietta Aluminum Company, Torrance, California.

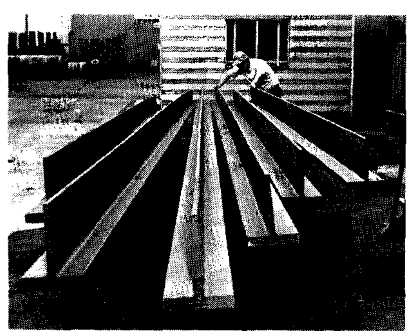


FIGURE 34. LARGE STEEL STRUCTURAL EXTRUSIONS

Photo Courtesy Cameron Iron Works, Houston, Texas.

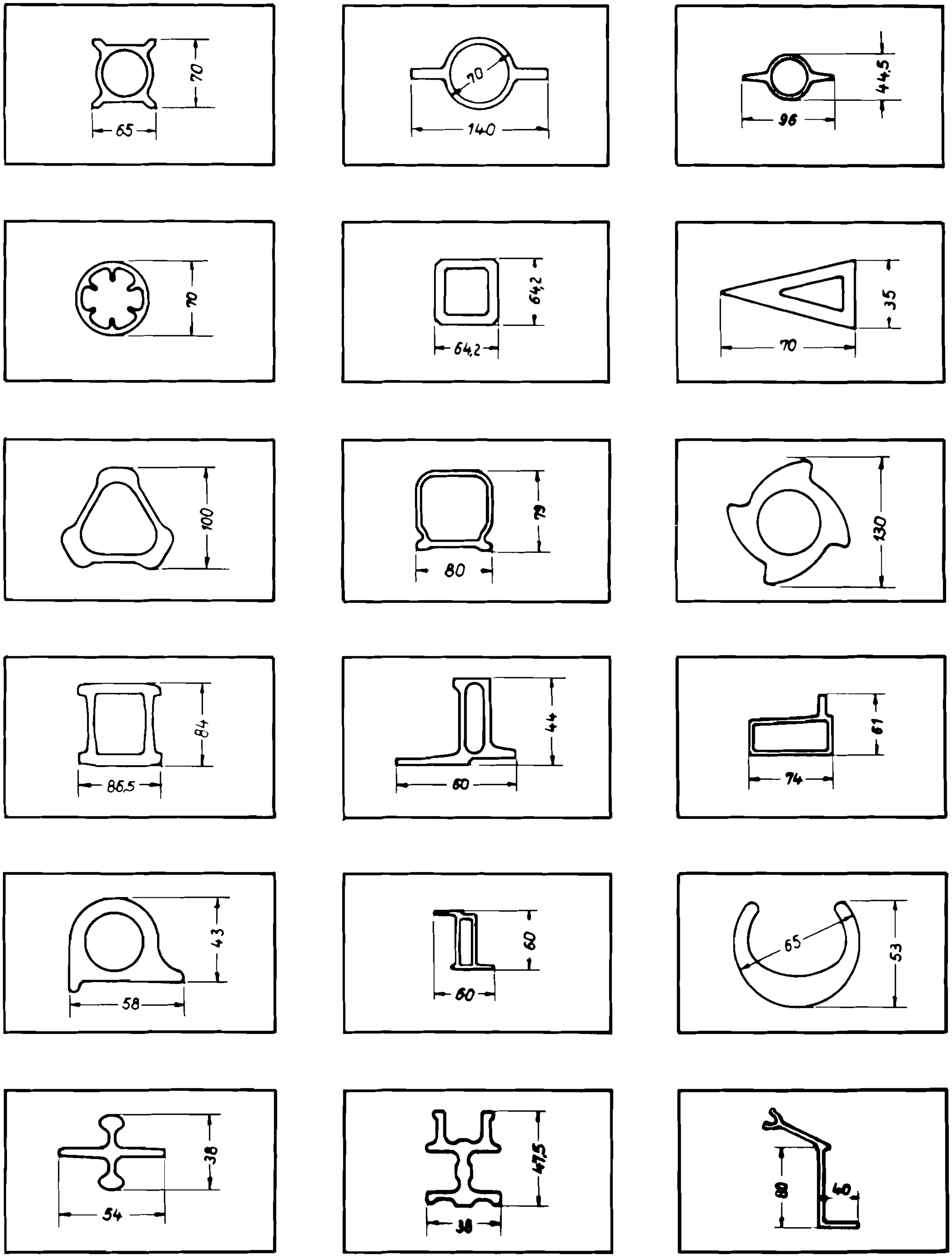


FIGURE 35. CARBON-STEEL SECTIONS EXTRUDED BY HOESCH-SCHWERTE A.G., SCHWERTE, GERMANY

Dimensions indicated in millimeters.

The techniques developed during the extensive effort resulted in the basic definition of extrusion parameters for extruding steel shapes in use today.

Simple sections such as T's, Z's, L's, and H's, as shown in Figure 31, are common along with the cruciform shape and other more complex shapes seen in Figures 32 and 33. Some very large structural extrusions are shown in Figure 34.

As an interesting contrast, Figure 35 shows some complex *low-carbon steel* shapes extruded by Hoesch-Schwerte A.G. in Germany for a variety of commercial applications. These configurations indicate a high degree of complexity achievable under closely controlled conditions with lower strength materials such as carbon steel.

Process Conditions Used

Listed in Tables 4 through 6 in flow chart form are the general extrusion conditions used in the extrusion of a variety of steels.

EXTRUSION OF BERYLLIUM

Beryllium is of interest to the aircraft and aerospace industry because of its high "strength-to-weight" ratio and its superior "Young's Modulus-to-weight" ratio. Figure 36

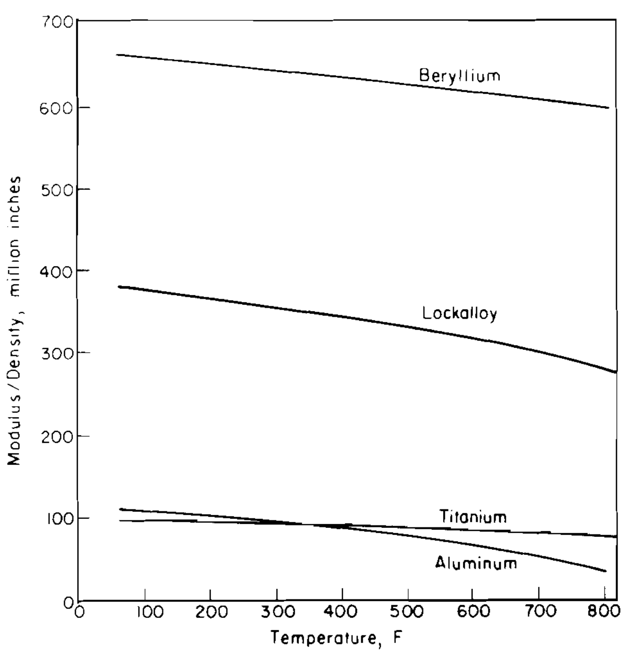


FIGURE 36. COMPARISON OF MODULUS/WEIGHT RATIOS FOR SEVERAL LIGHTWEIGHT ALLOYS

compares the modulus/weight ratio for beryllium, aluminum, titanium, and Lockalloy (a Be-Al alloy to be discussed later). Beryllium also retains many of these favorable properties at moderately elevated temperatures, and is of interest particularly in tubular form, in heat-transfer applications because of its high heat capacity. The use of beryllium is complicated, however, by its lack of ductility at room temperature and its high degree of anisotropy in wrought form. Fabrication requires the use of elevated temperatures and becomes complicated by the rapid oxidation of the beryllium and the toxicity hazard posed by this oxidation.

Because of the toxicity problem, the original work on rod and tube extrusion of beryllium employed canning techniques to prevent contamination and oxidation. In the early 1960's, however, an Air Force-sponsored program with Northrup Norair[25] was undertaken to attempt to establish techniques which would allow beryllium to be extruded into structural shapes without the expense of billet canning. Although these efforts met with some initial success, it was ultimately apparent that reproducible production techniques would not be possible using bare billets and conventional glass lubrication techniques. Thus, the program reverted to steel canning techniques still used today.

Some limitations in using pure beryllium have been mentioned: lack of biaxial ductility and relatively expensive procedures required in fabricating it into usable form. Other limitations include sensitivity to surface damage or defects, requirements for chemical etching after working or machining and poor weldability.

Lockalloy, a new alloy which eliminates many of these problems, was developed by Lockheed Missiles and Space Company in 1964.[41] It is a powder-metallurgy product containing 65 percent beryllium and 38 percent aluminum. As Figure 36 indicates, the modulus-to-weight ratio for this alloy is higher than that of titanium, and its general fabricability is greatly improved over that of pure beryllium. Sensitivity to surface damage is reduced and chemical etching is not necessary after machining or fabrication. Weldability is also good, but most important, formability is greatly improved.

Figure 37 shows some Lockalloy shapes after joggling and contour forming.[42] Copper-plated Lockalloy can be extruded around 900 F; comparable beryllium extrusion requires a steel can and 1800 F with its attendent contamination problems.

Initial efforts with pure beryllium were limited to extrusion of conventional T-, L-, and U-shaped channel sections such as shown in Figure 38. However, canning techniques have opened the way to extruding much more complex shapes. Nuclear Metals, Incorporated, has extruded a variety of unique structural shapes by the billet

TABLE 4. GENERAL PROCESSING DATA FOR EXTRUSION OF AISI 4340, PH14-8Mo, AND 18 PERCENT NI MARAGING STEELS

BILLET PROCESSING

Starting Stock

Vacuum arc remelt billet stock

Maximum grain size ASTM E112-1:	AISI 4340	5 to 6
	PH14-8Mo	6 to 7
	18 percent Ni maraging	1 to 3

Machining

63 microinch RMS finish

Precoating for Heating

None

Heating for Extrusion

60-cycle induction preheat to 1300 F

Dry nitrogen

Typical Extrusion Temperatures

1950 to 2250 - AISI 4340
1975 to 2250 - PH14-8
2050 to 2100 - 18 percent Ni maraging

EXTRUSION CONDITIONS

Lubrication

Container glass	200 mesh/leadless glass/1450-1500 F melting range
Die glass	Leadless glass/1300-1400 F melting range
Glass wool	Yes

Tooling Temperature

Container	600 F
Die	Room temperature

Ram Speed

AISI 4340	PH14-8Mo	18 Percent Ni Maraging
5 ips	4 ips	2.2 ips

Tooling Materials

Container liner	H-12 tool steel - 16 microinch RMS bore finish
Dies	Cobalt-base ALX-6 plus 0.007/0.008-inch ZrO_2 Rokide coating – polished to 16-microinch RMS
Die bolsters	Not available
Stem	H-12 tool steel - 47 to 50 R_c

POSTEXTRUSION PROCESSING

Deglass (or descale)

Shot blast plus standard pickle and caustic bath treatment

Remove Surface Oxides

Detwist and Stretch Straighten

50-ton hydraulic press with 4000-foot-pound detwisting torque

TABLE 5. GENERAL PROCESSING DATA FOR EXTRUSION OF PH15-7, H-11 TOOL STEEL

BILLET PROCESSING

Starting Stock
PH15-7 air melt or consumable-electrode ingot
H-11 electric arc melted; extruded or hot rolled

Machining
Centerless ground

Precoating for Heating
ALG-18 for PH15-7
None for H-11

Heating for Extrusion
Globar air heating
Typical Extrusion Temperatures

PH15-7	2200 F
H-11	2250 F

EXTRUSION CONDITIONS

Lubrication

Container glass	ALG-12
Die glass	ALG-8
Glass wool	ALG-13 glass wool

Tooling Temperature

Container	800 to 1000 F
Die	Room temperature

Ram Speed
Not available

Tooling Materials

Container liner	H-12 46-48 R_c
Dies	ALX-6
Stem	Type S-1

POSTEXTRUSION PROCESSING

Deglass (or descale)
Pickle and bright dip

Remove Surface Oxides

Detwist and Stretch Straighten
H-11-anneal before straightening

TABLE 6. GENERAL PROCESSING DATA FOR EXTRUSION OF A286

BILLET PROCESSING

Starting Stock
Consumable-electrode vacuum-remelted stock, forged and rolled to size

Machining
Centerless ground 80-microinch, RMS, finish

Precoating for Heating
None

Heating for Extrusion
Induction

Typical Extrusion Temperature
2110 F

EXTRUSION CONDITIONS

Lubrication

Container glass	FB50*
Die glass	FB50* + oildag

*Chemical composition FB-50 fiberglass, percent

SiO_2	58.20	CaO	13.20
Al_2O_3	13.50	ZrO_2	.33
Fe_2O_3	.23	Na_2O	.36
MgO	4.60	B_2O_3	9.40

Tooling Temperature

Container	450 F
Die	750 F

Ram Speed
5.5 ips

POSTEXTRUSION PROCESSING

Deglass (or descale)
Not available.

Remove Surface Oxides
Not available.

Hot Detwist and Stretch Straighten
Not available.

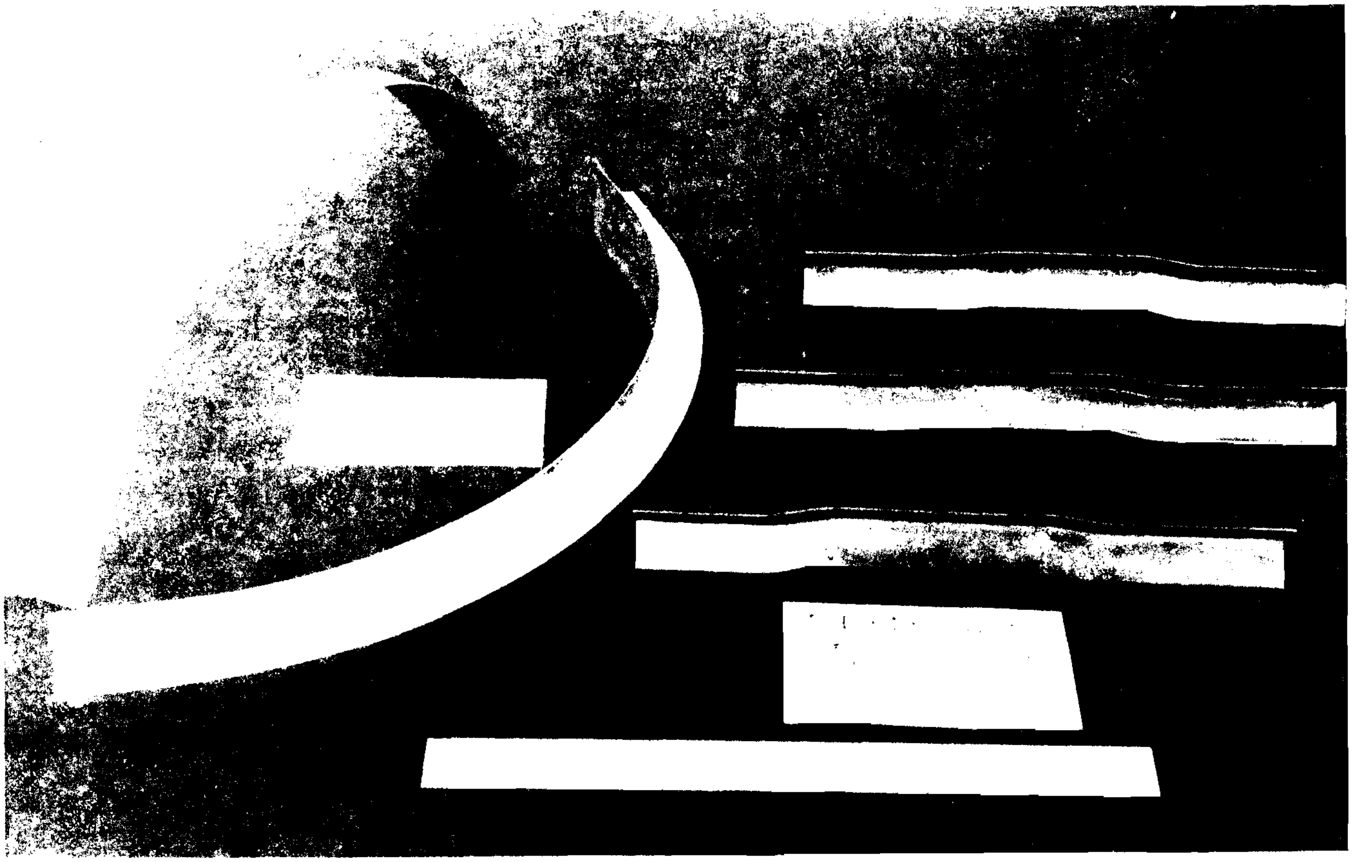


FIGURE 37. LOCKALLOY SHAPES AFTER JOGGLING AND FORMING[42]

canning method[42]. Several of these extruded shapes and finned tubing components are shown in Figure 39.

Processing Conditions Used

Tables 7 and 8 contain extrusion processing data for beryllium and Lockalloy shapes.

EXTRUSION OF REFRACTORY METALS

A variety of refractory metals (so named because of their melting points of 4300 to 6300 F and their exceptional strength at elevated temperatures) has extruded in the continuing development of manufacturing processes for high-strength materials applicable to aircraft and aerospace systems. While none of the refractory metals – molybdenum, columbium, tantalum, or tungsten – have been investigated to any degree in their unalloyed form, alloys of these materials have been investigated because of their greater high-temperature strength than the unalloyed materials. Interest has also centered around the extrusion of tubing in certain alloys, again for aerospace applications.

Concurrent studies conducted in the early 1960's involved extrusion of the following alloys:

- Columbium alloy D-31 (Cb-10Ti-10Mo-.1C) – shapes[44]
- Columbium alloy D-43 (Cb-10W-1Zr-.1C) – tubular products[45]
- Tantalum-10 tungsten and Ta-30Cb-7.5V -- shapes[46]
- Tungsten-3Mo – shapes[47]
- Molybdenum TZM alloy (Mo-0.5Ti-0.09Zr-0.03C) – shapes[23].

Needless to say, the requirements for preheating billet material to temperatures on the order of 3000 to 4000 F create extensive problems in tool and die life. However, the development of glass compositions for lubricants, the use of zironcia-coated and solid-ceramic dies, and extrusion at very high extrusion speeds, yield surprisingly good results.

A major problem in extruding columbium and tantalum is their extreme susceptibility to contamination in the air when heated to elevated temperatures. However, the practices developed by DuPont in extruding D31 alloy shapes demonstrated that through (1) close control of billet heating, (2) rapid transfer of the billet into the press, and (3) high extrusion speed, shapes could be

TABLE 7. GENERAL PROCESSING DATA FOR EXTRUSION OF BERYLLIUM

BILLET PROCESSING

Starting Stock
Hot vacuum-pressed powder - Grade QMV-200 (loose powder packed to density of 1 g/cc in steel can used successfully)

Machining
Beryllium machined to 32 RMS on OD before canning - Steel can polished on ID. No evacuation before sealing can.
Steel can 0.1-inch thick, 0.020-inch-thick copper plate on OD

Precoating for Heating
None

Heating for Extrusion
Available source using reducing atm or inert gas to prevent billet surface sealing
Typical Extrusion Temperatures
1625 to 1950 F (B2)
1700 to 1875 F (B4)

EXTRUSION CONDITIONS

Lubrication

Container glass	Mica-base lube called Necrolene Aqua Dag

Tooling Temperature

Container	825 to 900 F
Die	Room temperature

Ram Speed
2 ips (minimum)

Tooling Materials

Container liner	
Dies	M2 or EDS cobalt-base (cast dies)
Die bolsters	

POSTEXTRUSION PROCESSING

Deglass (or descale)
Pickle to remove steel sheath

Remove Surface Oxides

Detwist and Stretch Straighten
Utilize internal and external straightener — detwist and stretch straightening not applicable

TABLE 8. GENERAL PROCESSING DATA FOR EXTRUSION OF LOCKALLOY

BILLET PROCESSING

Starting Stock
Powder metallurgy product preextruded to provide billet material

Machining
60-RMS finish on surface-nose end chamfered

Precoating for Heating
(1) Degrease in trichlorethylene
(2) Etch surface in 10 percent solution HCL
(3) Ultrasonic clean
(4) Flash plate in copper cyanide at 110 F; 45 amperes/sq foot for 20 minutes
(5) Plate 0.015 to 0.020-inch copper from copper sulfate both at 140 F - 45 amperes/sq foot
(6) Outgas copper-plated billet at 10^{-4} 4 hours at 350 F
(7) Heat billet to 240 F
(8) Apply by spraying coating of 20 WS_2, 20 graphite, 60 water + 20 percent waterglass.

Heating for Extrusion
Available sources
Typical Extrusion Temperatures
900 F to 950 F

EXTRUSION CONDITIONS

Lubrication

Container	Bentonite grease + WS_2 + graphite
Die	Same as billet

Tooling Temperature

Container	900 F
Die	900 F

Ram Speed
Up to 2.5 ips for T-section
Up to 4.5 ips for L-section

Tooling Materials/Design

Container liner	Standard tool steel
Dies	Standard tool steel – flat faced with 1/2-inch x 45-degree cone ring. Die approach radius of 1/8 inch, land length of 1/32 inch. Surface finish 8 microinches, RMS.
Die bolsters	Standard

POSTEXTRUSION PROCESSING

Deglass (or descale)
Pickle in 50 HNO_3–50 H_2O solution to remove copper

Remove Surface Oxides
Not available

Hot Detwist and Stretch Straighten
After vacuum anneal at 1100 F for 24 hours, heat to 800 F and stretch straighten or hot-press straighten.

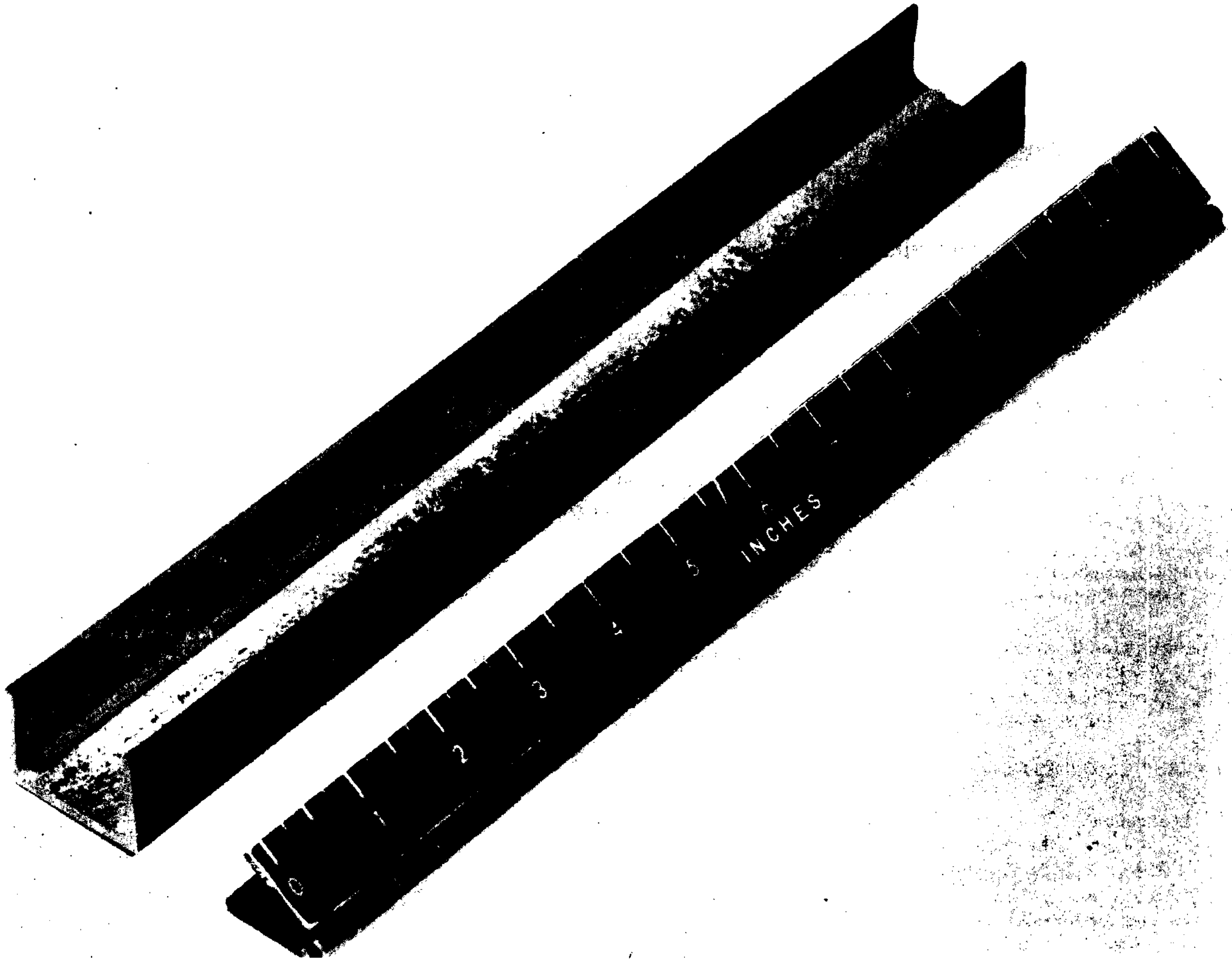


FIGURE 38. AS-EXTRUDED BERYLLIUM CHANNEL SHAPE[25]

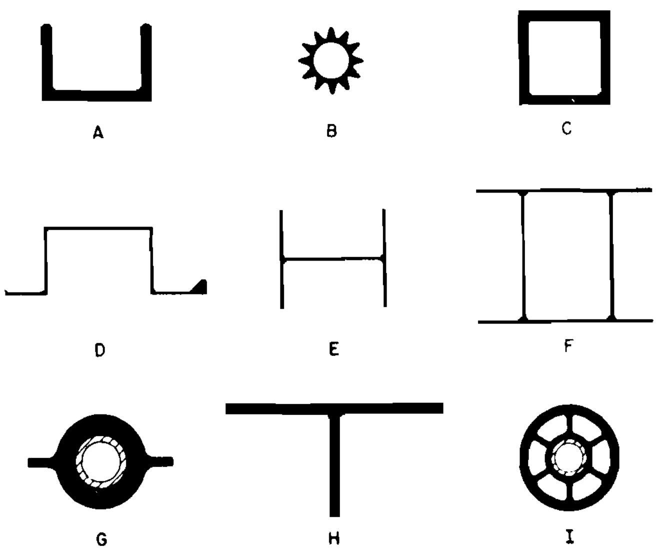


FIGURE 39. BERYLLIUM SHAPES EXTRUDED BY FILLED-BILLET METHOD[43]

extruded which had a contamination layer of only about 0.005 inch. This layer could be removed easily by pickling even though billets were heated to temperatures as high as 3300 F.

It is typical for refractory metal castings to have a large grain size. Thus, the castings must be refined before extrusion if good surface finish is to be obtained and acceptable material properties are to be realized. Thus, the first step in processing a cast ingot to an extruded shape usually involves canning the cast ingot and breakdown extrusion at an extrusion ratio on the order of 4:1. Subsequently, the canning material is removed and the billet is reprepared for shaped extrusion. Requirements for initial ingot breakdown could likely be bypassed if powder-metallurgy billets can be used.

Successful extrusion of refractory metal shapes is dependent upon prevention of contamination during billet heating and transfer to the extrusion press, use of tooling temperatures between 750 and 1000 F, and very high

FIGURE 40. D31 COLUMBIUM ALLOY TEE-SHAPE EXTRUSION[44]

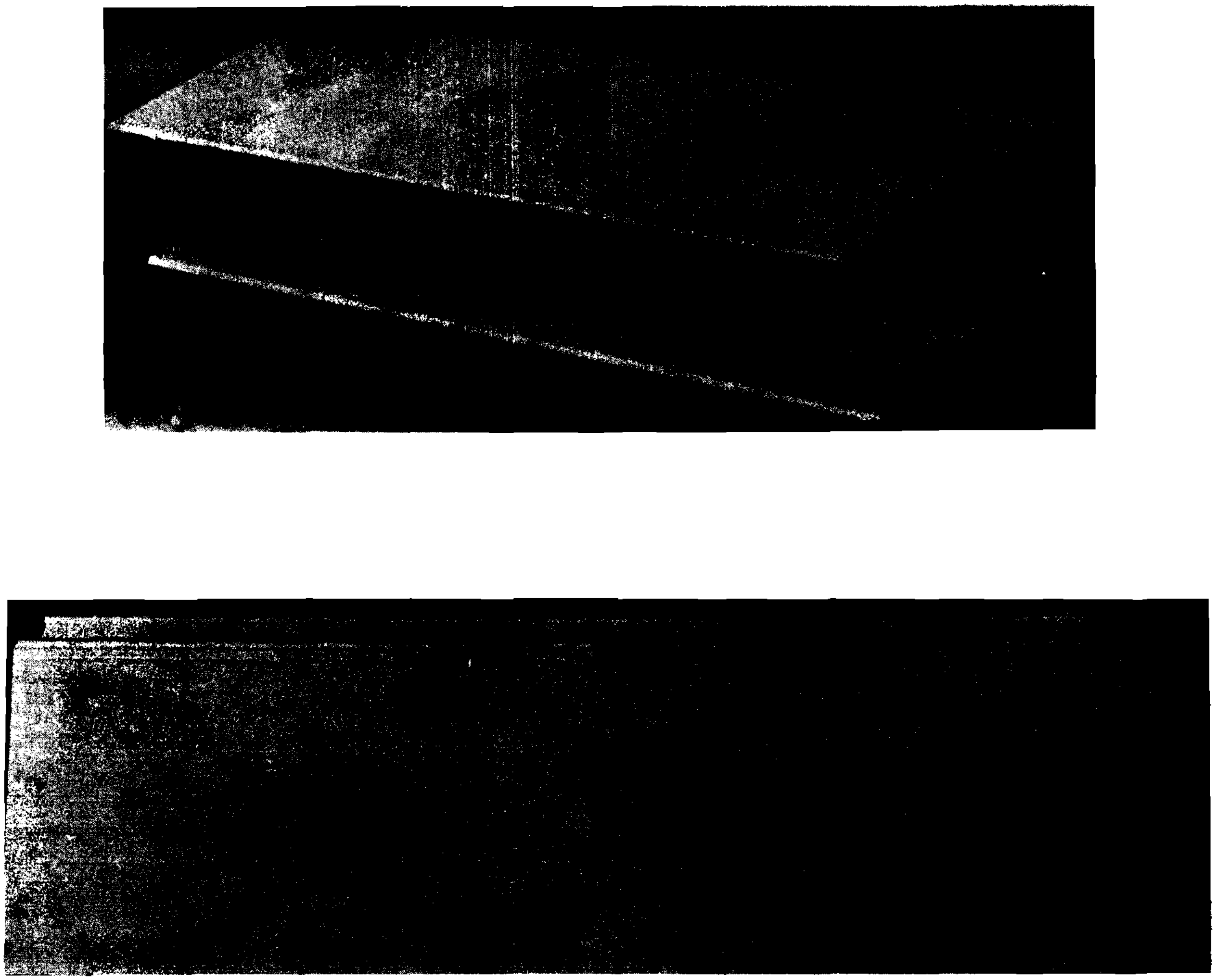


FIGURE 41. MOLYBDENUM TZM ALLOY H-SECTION AS-EXTRUDED[23]

FIGURE 42. COLUMBIUM ALLOY D43 EXTRUDED TUBING[45]

extrusion speeds. Under these conditions, extruded shapes have been made from a number of alloys in maximum lengths of about 10 feet. With the very high temperatures used, long lengths do not appear practical because of the problems in die wear that would be encountered.

To date, aerospace applications for refractory metal shapes are nonexistent. However, in the event that markets develop for these alloys, the techniques established in these series of Air Force-sponsored programs can be utilized. Samples of refractory metal shapes are shown in Figures 40, 41, and 42. Figure 40 shows a D31 columbium alloy T-section. Figure 41 shows a molybdenum TZM alloy H-section as extruded. Some refractory metal tubing also has been extruded, in particular the columbium alloy D43 shown in Figure 42. Tube shells are hot extruded followed by tube drawing operations.

Processing Conditions Used

Tables 9 through 12 contain extrusion process data for columbium, molybdenum, and tantalum alloys and unalloyed tungsten which have been extruded into shaped products.

EXTRUSION OF NICKEL BASE/ COBALT BASE SUPERALLOYS

The extrusion of superalloys has been aimed primarily at ingot breakdown of cast materials, particularly with alloys of limited ductility. Some extrusion of thick walled tubes has also been reported. In both instances, extrusion ratios have generally been limited to below 7:1.

In contrast to the thin-section *alphabet-type* shapes investigated in most other structural materials of interest to the aerospace industry, research in superalloy shape extrusion has been primarily aimed at the production of relatively thick sections for use in the gas turbine engine applications such as seals, flanges, and rings. Extrusions are subsequently ring rolled, welded, and machined to finish dimensions.

The principal difficulty encountered in extruding nearly all superalloys is their limited hot working range. Table 13 shows hot workability ranges for several nickel-base superalloys[48]. If temperatures used are too high, hot shortness is encountered and cracking results. If temperatures are too low, available extrusion pressures are quickly exceeded. Even when optimized extrusion

TABLE 9. GENERAL PROCESSING DATA FOR EXTRUSION OF COLUMBIUM ALLOYS D-31, B-66*-D-43*

BILLET PROCESSING

Starting Stock

(1) Double consumable-electrode vacuum-arc-melted ingot
(2) Can in mild steel and extrude at 4:1 ratio – 1900 to 2100 F (2000 F for B-66, 2000 to 2100 F for D-43)
(3) Machine surface to remove steel
(4) Attach pure columbium nose piece with 45-degree edge chamfer (D-31)

Heating for Extrusion

Heat 200 F/minute by induction under argon atmosphere
Typical Extrusion Temperatures

D-31	3200 to 3300 F
B-66; D-43	3000 to 3200 F

EXTRUSION CONDITIONS

Lubrication

Container glass	(D-31) – C and D glass; (D-43) – C glass in bore; (B-66) – G Glass on OD
Die glass	MoS_2 + Oil Dag in container
Glass wool	(D-31) – FW glass wool with conical die; (D-43) and (B-66) F glass

Tooling Temperature

Container	850 to 950 F
Die	750 F

Ram Speed

3 to 6 ips

Tooling Materials

Container liner	Not available
Dies	Conical entry, H-13 steel, 46/48 R_c zirconia coating 0.030/0.035 inch thick
Mandrel	H-13 steel: 49/51 C
Die bolsters	Not available

POSTEXTRUSION PROCESSING

Deglass (or descale)

Sandblast

Remove Surface Oxides

Detwist and Stretch Straighten

Heat to 300 F and straighten on 150-ton press. Elongation of 0.25 percent.

*Tube alloys.

TABLE 10. GENERAL PROCESSING DATA FOR EXTRUSION OF MOLYBDENUM ALLOY TZM

BILLET PROCESSING

Starting Stock
Consumable-electrode arc-melted material extruded, at low ratio, recrystallized at 3000 F for 2 hours, rolled, heat treated 1 hour at 2900 F.

Machining
Pressed and sintered molybdenum nose piece 1 inch long attached to TZM billet by threaded stud. 1-inch nose radius.

Precoating for Heating
None

Heating for Extrusion
Induction with inert gas
Typical Extrusion Temperature
3300 F

EXTRUSION CONDITIONS

Lubrication

Container glass	Al-30-45/-325 mesh
Die glass	Al-P-56, Al-N-56
Glass wool	

Tooling Temperature

Container	500 F
Die	

Ram Speed
1.7 ips

Tooling Materials

Container liner	Nitrided H-13 tool steel
Dies	Zirconia coatings 0.05 inch thick on Potomac M tool steel 49-51 R_C. 120-degree included die-entry and angle-entry radii for shapes 1/16 inch to 3/16 inch
Die bolsters	

POSTEXTRUSION PROCESSING

Deglass (or descale)
Sandblast

Remove Surface Oxides
None

Detwist and Stretch Straighten
Hot straighten at 600 F

TABLE 11. GENERAL PROCESSING DATA FOR EXTRUSION OF Ta-10W

BILLET PROCESSING

Starting Stock
(1) Double EB melted ingot
(2) Machine surface – remove 1/4 inch per side
(3) Forge ingot at 2300/2400 F or extrude at 3:1 ratio
(4) Machine OD
(5) Can in molybdenum with molybdenum nose plug

Precoating for Heating
None

Heating for Extrusion
Induction heating in argon
Typical Extrusion Temperatures
3400 – 3500 F

EXTRUSION CONDITIONS

Lubrication

Container glass	1602-1 – Applied under argon
Die glass	1602-10
Glass wool	

Tooling Temperature

Container	900 F
Die	500 F

Ram Speed
10 ips (minimum)

Tooling Materials

Container liner	Not available
Dies	(1) Solid zirconia insert – shrunk in ring
	(2) Zirconia coated H-13 steel 49/51 R_c
Die bolsters	Not available

POSTEXTRUSION PROCESSING

Deglass (or descale)
Not reported

Remove Surface Oxides
Not available

Hot Detwist and Stretch Straighten
Not reported

TABLE 12. GENERAL PROCESSING DATA FOR EXTRUSION OF TUNGSTEN AND W-3Mo

BILLET PROCESSING

Starting Stock
Pressed and sintered block

Machining
Not reported

Precoating for Heating
Glass/bentonide/clay/water mixture sprayed on billet preheated to 400 F

Heating for Extrusion
Induction heating under argon
Typical Extrusion Temperatures

W	3720 F
W-3Mo	3650 F

EXTRUSION CONDITIONS

Lubrication

Container glass	Al-11-45
Die glass	Al-L-56
Glass wool	

Tooling Temperature

Container	Not reported
Die	Not reported

Ram Speed
1.7 ips

Tooling Materials

Container liner	Not available
Dies	H-13 – 52/54 R_C nitrided + 0.002/0.003 nichrome + 0.040 inch zirconia. 100/120-degree entry angle
Die bolsters	Not available

POSTEXTRUSION PROCESSING

Deglass (or descale)
Grit blasted

Remove Surface Oxides
Not available

Hot Detwist and Stretch Straighten
Not reported

temperatures are defined, it is still necessary to extrude somewhat slowly so that the adiabatic heat from the deformation process does not raise the overall billet temperature into the hot short range. Since the composition of these alloys is complex and intermetallic phases are relied upon for optimizing grain size and mechanical properties in the final product, care and selection of hot-working conditions becomes extremely important.

TABLE 13. HOT-WORKABILITY RANGES FOR PRECIPITATION-HARDENED NICKEL-BASE SUPERALLOYS[48]

Alloy	Hot-Workability Range, F			
	Lower Limit		Upper Limit	
	Minimum	Maximum	Minimum	Maximum
M-252	1800	1850	2150	2200
Rene 41	1800	1900	2150	2200
Alloy 718	1700	1850	2050	2150
Udimet 500	1900	1900	2150	2175
Udimet 700 (Astroloy)	1900	2000	2075	2200
Waspaloy	1800	1850	2150	2200
Inconel X	1700	1850	2175	2200

Todays extrusion of superalloys uses the conventional glass lubrication process. However, a successful program conducted in the mid-1960's by TRW[48], defined extrusion practices for producing both Waspaloy and Inconel 718 alloy shapes of 3-square-inch cross-sectional area in lengths of 15 feet using nonglass lubrication techniques. Figure 43 shows the shapes extruded on this program. To the author's knowledge, however, these techniques have not been utilized in production by commercial extruders primarily because their operations for extruding other materials utilize glass lubrication techniques and thus, these conditions are also used for extruding superalloys.

Extrusions used in jet engine rings are always vacuum arc melted and in some instances double arc melted to prepare a high-quality starting ingot. Generally speaking, these ingots undergo some preforging or cogging to modify the cast grain structure before use as billet extrusion material. Some large cast ingots are pre-extruded to rounds for subsequent use as extrusion billet material.

This grain refinement, of course, ultimately results in better surface finish on the final extruded product. In the early days some billets were canned, primarily for ingot breakdown. Canning techniques are not used, however, in producing shaped extrusions.

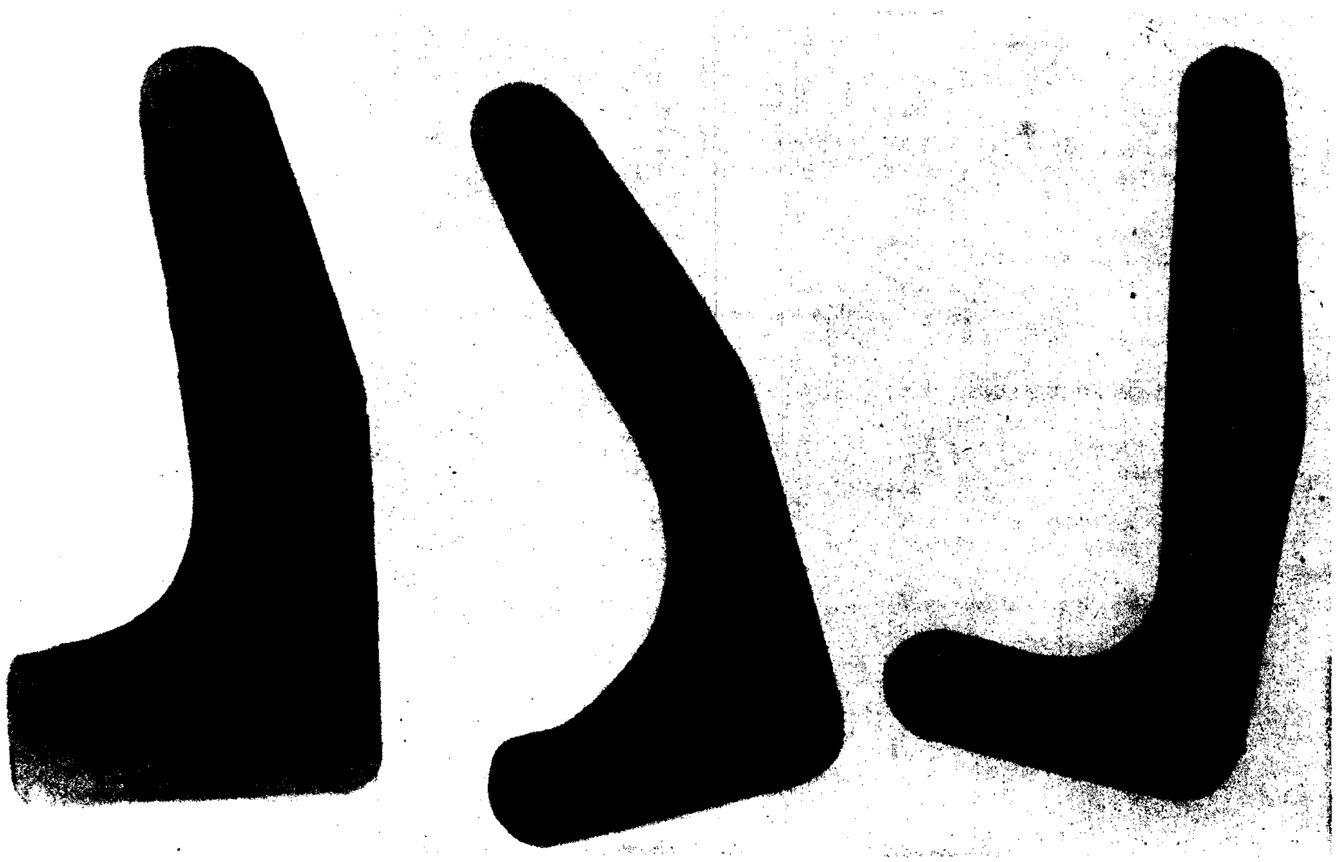


FIGURE 43. WASPALOY AND INCONEL 718 EXTRUSIONS[48]

TABLE 14. GENERAL PROCESSING DATA FOR EXTRUSION OF INCONNEL 718 AND WASPALOY

BILLET PROCESSING

Starting Stock
Vacuum-arc melted, forged to billet

Machining
Surface machined

Precoating for Heating
None

Heating for Extrusion
Salt bath
Typical Extrusion Temperatures

Inco 718	1925 F
Waspaloy	2050 F

EXTRUSION CONDITIONS

Lubrication

Container	Fiske 604
Die Pad	Graphite/Cr_2O_3/Sodium Silicate/ Cu Phthalocyanine

Tooling Temperature

Container	800 F
Die	800 F

Ram Speed
1.5 ips (Waspaloy)
.25 ips (718 Inco)

Tooling Materials

Container liner	Not available
Dies	(1) Zirconia coated tool steel
	(2) Cobalt-base EDX alloy insert with zirconia coated H-13 tool-steel entry cone
Die bolsters	Not available

POSTEXTRUSION PROCESSING

Deglass (or descale)
Grit blasted

Remove Surface Oxides
Not available

Hot Detwist and Stretch Straighten
Not reported

Billets may be heated by conventional fuel-fired furnaces, induction heating, or salt-bath heating. Some problems were encountered in the past with induction heating as a result of too rapid increase in temperature which caused cracking due to the low thermal conductivity of superalloys. Salt-bath heating is somewhat slower, thus, providing more control of heating of the extrusion billet. For nickel base alloys, as it is important to avoid contamination by sulfur, fuel-fired furnaces must be selected with care.

Controlled heating is exemplified by reports of heating some highly alloyed materials at rates not to exceed 150 to 200 degrees F per hour to extrusion temperatures on the order of 1800 F to 2000 F. These long heating times significantly restrict production rates possible in extruding these materials.

Processing Conditions Used

Table 14 contains extrusion processing data for extrusion of two nickel-base alloys.

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SECTION 2

FORM ROLLING OF SHAPES

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Page

SECTION 2

FORM ROLLING OF SHAPES

PROCESS HISTORY AND BACKGROUND

It is advisable at the outset to differentiate between *form rolling* and a comparable process known as *roll forming*. Form rolling involves substantial metal flow and reduction in thickness, e.g., rolling an airfoil section from a round bar. Roll forming is essentially bending and/or reforming a strip or bar to change its profile or shape but not its cross-sectional area, e.g., roll forming an L-section from flat strip.

Form rolling produces no chips, and yield can be as high as 90 percent with average yield over 80 percent for net weight shipped-versus-initial starting stock weight. The waste is limited to saw kerf, end croppings and an occasional cobble. Because the end product is a "net" shape with dimensions, contour, surface finish, and metallurgical properties of the finished part, no additional machining is required to achieve dimensional tolerances or surface conditions including finish and metallurgical considerations.

Form rolling, as applied to structural shapes, is a relatively new concept, although the actual process goes back many years. During the late 1880's, the jewelry industry form rolled decorative shapes in precious metal wire and tubing. These were primarily shapes such as ovals, squares, rectangles, and flats in solid precious metals or base metals with precious metal cladding, small sections such as bracelet stock and optical frame and hinge wire were produced (see Figure 44). By the mid-1920's the state of the art was well advanced in the jewelry trade, and many organizations were making fancy shapes and patterns by form rolling. The products varied from small ornamental patterned wire, as small as 0.010 inch wide, to bracelet stock as large as 1 inch wide. These sections were fairly thin, usually under 1/16 inch, and their rolled-on patterns simulated engraving. Patterned and/or shaped wire for the optical trade was a large part of the business.

During this period, form rolling was accomplished on small 2-high rolling mills, and in Turk's-head machines. Most of the finishing was done in Turk's-heads, with either powered rolls or by drawing through the rolls. The product was supplied as straight lengths or coiled stock depending upon configuration and application.

In the early 1940's, form rolling was adapted to materials other than precious metals; first as substitutes for jewelry items due to the wartime shortage of copper

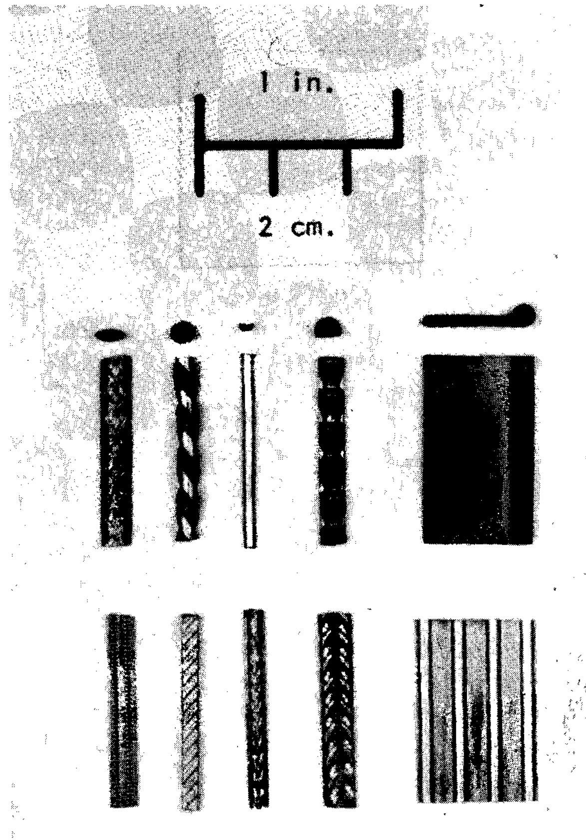


FIGURE 44. TYPICAL FORM-ROLLED JEWELRY SHAPES

and nickel-base alloys which were usually used as core materials, and then for actual manufacture of items for the war effort. Initial efforts, first with carbon steels and later with stainless steels, were expanded with the creation of separate form rolling facilities devoted entirely to nonjewelry applications.

The process is applicable to most wrought metals. A wide variety of shapes in a broad range of dimensions have been form rolled. Limitations in shape sizes and product length are functions of material handling and equipment capability, and both are constantly being upgraded.

PRESENT COMMERCIAL PRACTICES

The basic process is well-established and design concepts using form-rolled shapes benefit from the characteristics of the process that enable production of complex shapes economically in long lengths from a variety of

materials to close tolerances without machining. These characteristics as applied to high-strength materials are as follows:

- As grain flow pattern is similar to that resulting from forging, there is no cutting of flow lines or end grain exposure at the surface of fillet radii as happens when parts are machined from either extrusions or bar stock.
- Consistency of shape and dimension from one part to another is considerably improved over that possible by any other known method which does not entail metal removal.
- Surface finish is superior to that resulting from extruding or drawing through a die.
- Dimensional accuracy and tolerances are superior to those of extrusions and drawn shapes in stainless steel and superalloy materials.
- Material costs are reduced and material is conserved. It has been estimated that the material required for form rolling structural shapes in superalloy materials in long lengths is about half that required for machined extrusions, and one-third or less for machining from bar stock. Also, the manufacturing costs are greatly reduced since most of the machining labor to achieve a final part is eliminated.)

A wide variety of materials are processed. Table 15 includes a number of typical materials which have been form rolled. These include most types of stainless steel in the 200 and 400 series; superalloys such as the various Inconels, Hastelloy-X, Waspaloy, A-286; carbon and alloy steels, tool steels; and nonferrous materials such as titanium, copper, and copper-base alloys. In addition, development work is progressing in processing materials such as titanium alloys, Udimet 700, and René 41.

Starting material is usually centerless ground round bar, or cold rolled strip. This material is carefully inspected to assure freedom from pits, seams, laps, slivers or

TABLE 15. MATERIALS CURRENTLY BEING FORM ROLLED

AISI 1018	Hastelloy C
AISI 4130	Hastelloy X
AISI H-11 Tool Steel	A-286
AISI 403	Ph 15-7 Mo
AISI 321	Waspaloy
AISI 347	Greek Ascoloy
AISI 403	N-155
AISI 405	19-9-DL
AM 350	L-605
Inconel X	Titanium AMS 4921
Inconel 718	Copper and Copper Base Alloys
Inconel 722	

other surface imperfections. The bar or strip is then processed through several steps on the various pieces of form rolling equipment until the desired configuration is attained. The processing procedure for structural shapes is depicted in Figure 45.

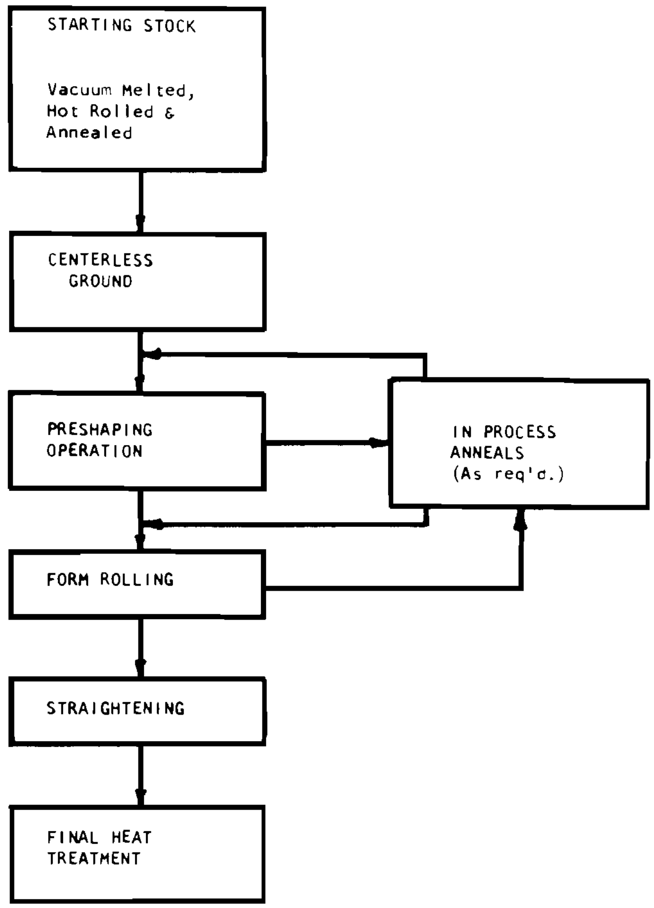


FIGURE 45. TYPICAL PROCESSING SCHEDULE FOR FORM ROLLING OF SHAPES

Depending upon the workability of the material, intermediate anneals may be required. To retain the integrity of the starting material, these anneals are performed in hydrogen atmosphere, vacuum, or other inert atmospheres.

Form rolling of complex, close-tolerance shapes present certain technological difficulties depending on the particular material and/or configuration under consideration. Both qualitative and quantitative differences are associated with processing a single shape from different materials, or with processing different shapes from a single material. This is verified by reviewing the processing sequence for two recently developed shapes.

The resultant shape from each operation in the form rolling of an Inconel 718 "E" shape is presented in Figure 46. A centerless ground bar, approximately 1.25-inch

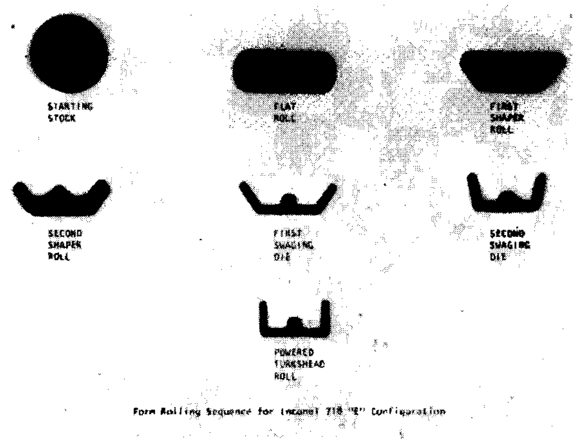


FIGURE 46. FORM-ROLLING SEQUENCE FOR INCONEL 718 "E" CONFIGURATION

diameter, is initially rolled to a round edged flat. The flat section is further reduced to a trapezoid. The leg formation is initiated through rolling to the second preshape in a number of passes with intermediate anneals. The second preshape is then swaged to sharpen the corners and flatten the bottom of the channel sections. The second swaging operation bends up the outside legs to permit easy insertion of the shape into the four-roll, powered Turk's-head for the final form-roll finishing operation. The length is then annealed, detwisted, and straightened and finally heat treated to produce mechanical properties. The resultant shape has finished contour and dimensions, surface finish that requires no metal removal, and mechanical properties as per specification for the finished part. The processing sequence includes a total of 12 anneals (1 final and 11 in-process) and 29 forming passes.

One of the most popular structural shapes is the "T" contour configuration. These shapes are characterized as having rather thin sections (approximately 0.049 inch thick) and various ratios of web height-to-leg width. The stationary die swaging technique has been used to produce ratios of 1:1 and 1.5:1 using different tooling designs and materials. The material-flow sequence is depicted in Figures 47 and 48. The final sizing to shape and dimensional tolerances and the high-quality surface finish were achieved in a powered Turk's-head.

The limitation on weight for close tolerance shapes is 30 pounds maximum for a length and 1.5 pounds maximum per foot of length. Heavier bars and larger cross sections are available as hot rolled products with increased tolerances. Weight and tolerances in this case are not well defined and depend upon the individual shape and material involved.

Typical dimensional tolerances for close tolerance shapes are as follows:

Contour:	±0.001 to ±0.005 inch
Thickness:	±0.002 to ±0.005 inch
Width and Height:	±0.005 to ±0.015 inch

The consistency of dimensions within a lot of material processed at one time will be about half the above tolerances. Since the tool surfaces are moving with the material, little or no die wear or scoring occurs and dimensions are not affected as they are with extrusion and drawing processes. Even with machining, tool or grinding wheel wear occurs along the length of a long piece which results in dimensional variation.

Typical maximum per foot straightness tolerances are:

Bow:	0.060 inch for as-rolled bars
	0.015 inch for stretch-straightened bars
Camber:	0.150 inch for as-rolled bars
	0.025 inch for stretch-straightened bars
Twist:	5 degrees for as-rolled bars
	1 degree for stretch-straightened bars

An additional advantage of form rolled shapes is that, since most processing is done cold, normal surface finish is bright and smooth. Surface finishes of 5 to 30 microinches, rms, are typical for as-rolled surfaces. Some parts require abrasive edge finishing to remove flash, or to deburr, etc. These finishes have a roughness of 30 to 60 microinches, rms.

An example of the dimensional uniformity obtainable by the process is illustrated in Figure 49. The airfoil section, form rolled from Hastelloy-C, is mounted in a shroud ring through a slot which conforms to the shape of the airfoil with brazing clearances. The long, thin trailing edge and the relatively thick shroud ring precluded punching the slot. To provide a method other than machining with cutting tools to produce the slot, which must fit the contour of the blade, lengths of airfoil were form rolled from copper-base material in the same rolls used to make the Hastelloy-C airfoil. These copper lengths were used as electrodes in electrical-discharge machining of the required openings. Since the electrodes were exact reproductions of the airfoil, no further fitting was required. This same technique is also applicable to almost any form rolled configuration.

The finish size of form rolled products is governed only by equipment capability and space provided. Straight lengths of 45 feet have been produced. Industry can supply stretch-straightened lengths up to 25 feet and heat-treated lengths up to 12 feet.

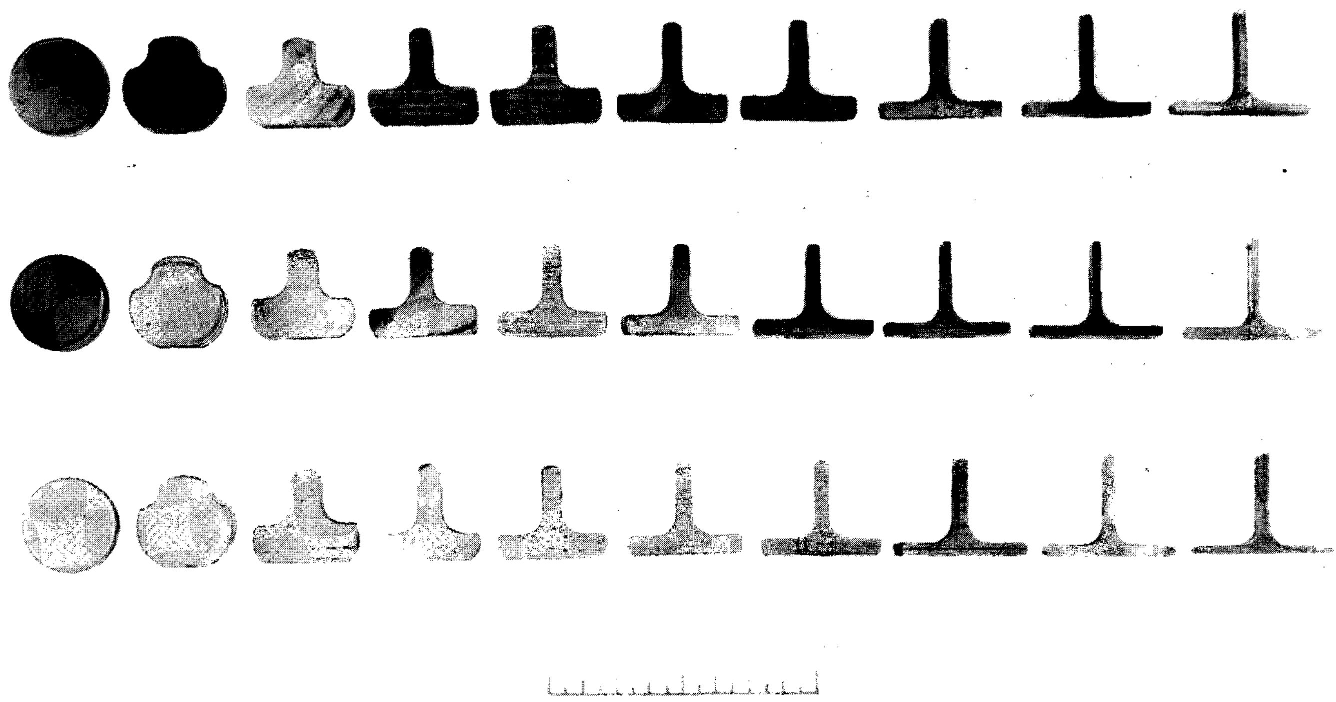


FIGURE 47. SECTIONS OBTAINED AFTER EACH MANUFACTURING STEP FROM HASTELLOY BAR

It should be pointed out that tooling design for form-rolling sequence is still an art and not an exact science. An acceptable product can be made only through tooling and process modifications based upon experience and judgments, and not on well-established engineering parameters. Thus, the development of analytical techniques to enable the prediction and calculation of roll pass sequences could greatly reduce tooling design costs and, ultimately finish part costs.

FORM-ROLLING EQUIPMENT

The basic form-rolling equipment is a 2-high rolling mill such as is shown in Figure 50. The mill pictured here is a No. ZF-2 Schmitz Rolling Mill with a variable-speed drive, and 9-inch-diameter working rolls. The shape may be completely processed in such a mill from round bar to finished shape, or other equipment may supplement the

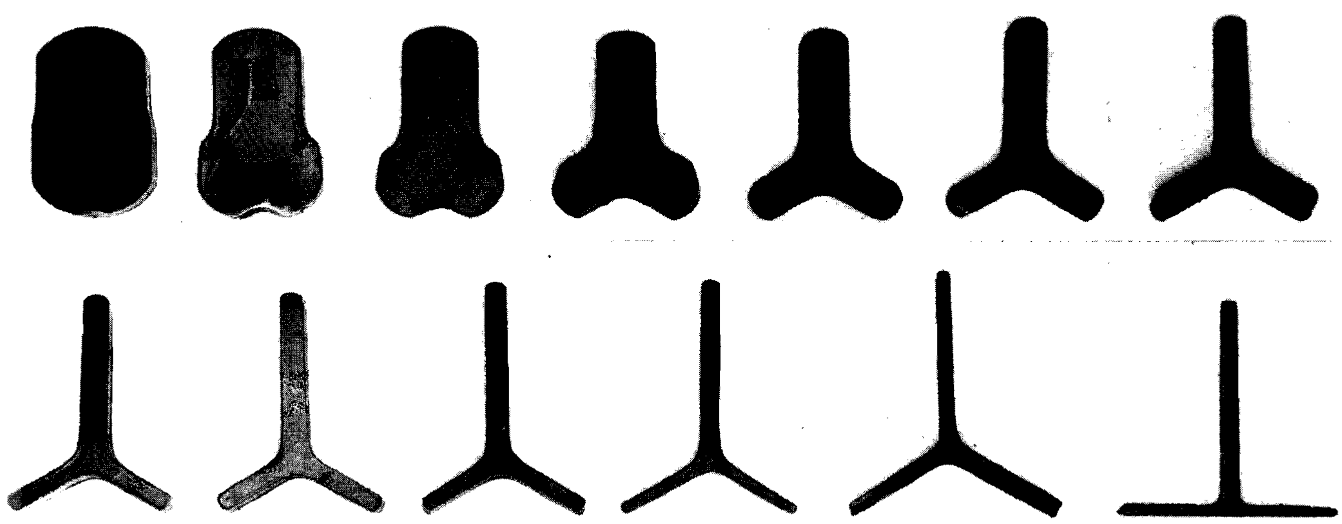


FIGURE 48. CROSS SECTIONS TAKEN AFTER EACH SWAGING STEP FROM RENÉ 41

mill for preshaping or finishing. A set of shaping rolls for the mill are shown in Figure 51.

The stationary-die swager shown in Figure 52 is used for preliminary breakdown or for intermediate processing. The stationary-die swager differs from the well-known rotary-die swager in that the spindle or die holder does not rotate. In the operation of the rotary die swager, as illustrated in Figure 53, the spindle, which holds the dies, rotates. As the dies move past the rolls which are held in a cage around the spindle, a projection on the hammers causes the dies to move together, producing the hammering action.

In a stationary-die swager, Figure 54, the spindle of the machine is held stationary, and the head-ring rotates causing the rolls in the roll cage to rotate around the spindle. As the rolls move past the high spot on the hammers, they cause the dies to move in and out striking the material in a manner similar to forging. With the rotary die swager, only round sections can be formed since the dies must move around the work striking it at a different point on the periphery on each successive stroke. The movement of the dies around the bar causes it also to rotate. Nonsymmetrical shapes can be formed in the stationary-die swager, since each die strokes the material in the same plane on successive blows, and the material does not rotate. The stationary-die swager has long been used primarily as a pointing machine to shape tapered sections such as file tangs or screwdriver ends. It has recently been adapted for straight feeding so that long, uniform-thickness, symmetrical or nonsymmetrical shapes can be formed. The metal flow, produced in a manner very similar to that of forging, provides uninterrupted grain flow along contoured surfaces, particularly around fillet radii. An example of a nonsymmetrical swaged structural shape is the 12-feet-long "E" configuration depicted in Figure 55.

With this equipment, high unit pressure achieved at the point of impact permits large reductions even with high-strength alloys. Since the surfaces are moving in relation to the material being formed, and increments of advance are relatively small, lubrication problems are minimal and tendencies for surface cracking and checking are reduced because die-to-metal surfaces are in compression.

The shape is often finished in either a draw-through or powered Turk's-head. In the draw-through Turk's-head, the power for moving the material through the rolls is supplied by a drawbench similar to those used for die drawing. The Turk's-head is mounted on one end and power is applied at the other end through a chain which draws the grasping jaws along the drawboard. In most modern equipment, a hydraulic cylinder provides the rawing tension, but the length of the cylinder is a

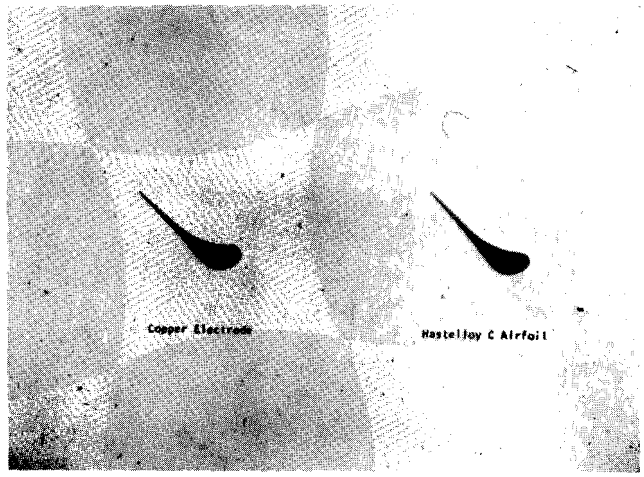


FIGURE 49. AIRFOIL SHAPE FORM ROLLED IN HASTELLOY X

Form-rolled copper electrode used to EDM ring-shroud opening for airfoil.

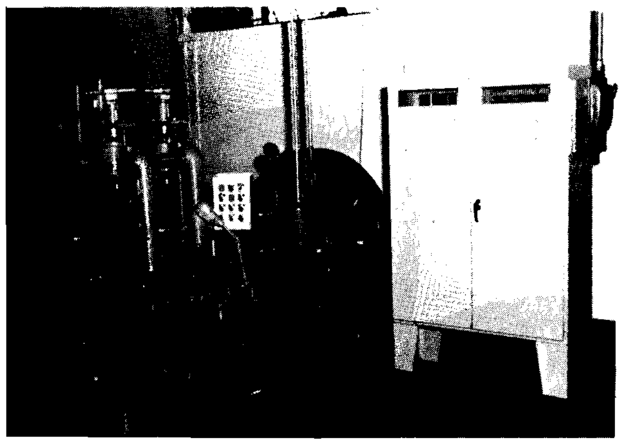


FIGURE 50. 2-HIGH FORM-ROLLING MILL

FIGURE 51. SHAPING ROLLS FOR FORM-ROLLING MILL

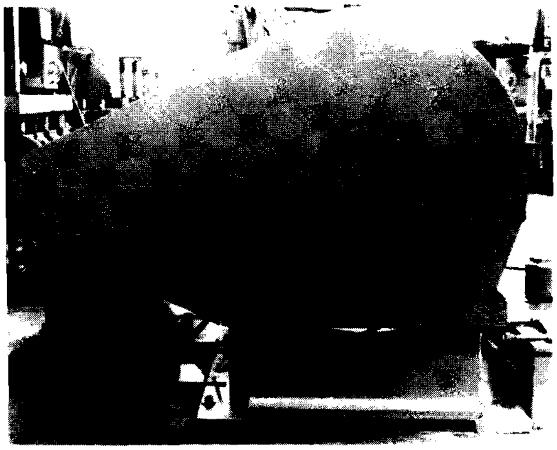


FIGURE 52. DIE SWAGER COMMONLY USED FOR INITIAL AND INTERMEDIATE BREAKDOWN IN FORM ROLLING

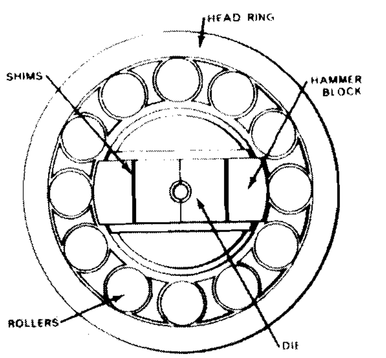


FIGURE 53. SWAGING PRINCIPLE WITH ROTARY-DIE SWAGER

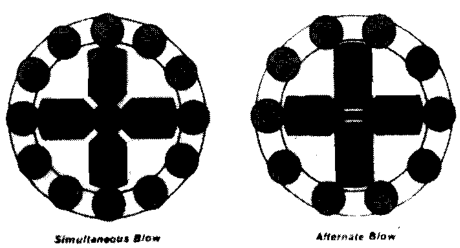


FIGURE 54. SWAGING PRINCIPLE WITH STATIONARY DIE SWAGER

FIGURE 55. E-SHAPED SECTION FORMED ON STATIONARY DIE SWAGER

limitation. Lengths of 20 feet are commonly swaged, but 60-foot lengths can be handled by lengthening the chain and draw table.

The principle of operation of the Turk's-head is shown in Figure 56. The operation resembles die drawing since the material is pulled through an opening. However, a very important difference is that the working surfaces (here, four adjustable rolls) move with the material as it is being reduced. This results in a very superior surface condition and maximum uniformity of dimensions.

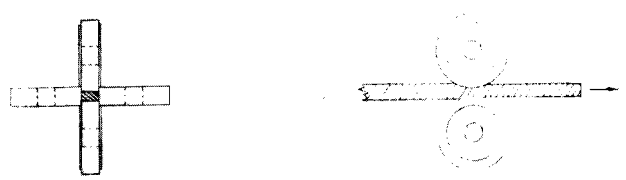


FIGURE 56. TURK'S-HEAD METHOD OF FORM ROLLING

In the powered Turk's-head, as shown in Figure 57, at least two of the rolls are power driven. These rolls, usually sufficient to move the section through the Turk's-head and, thus, removes length limitations of conventional drawing. In addition, entry into the rolls is easier because long leads or points are not needed.

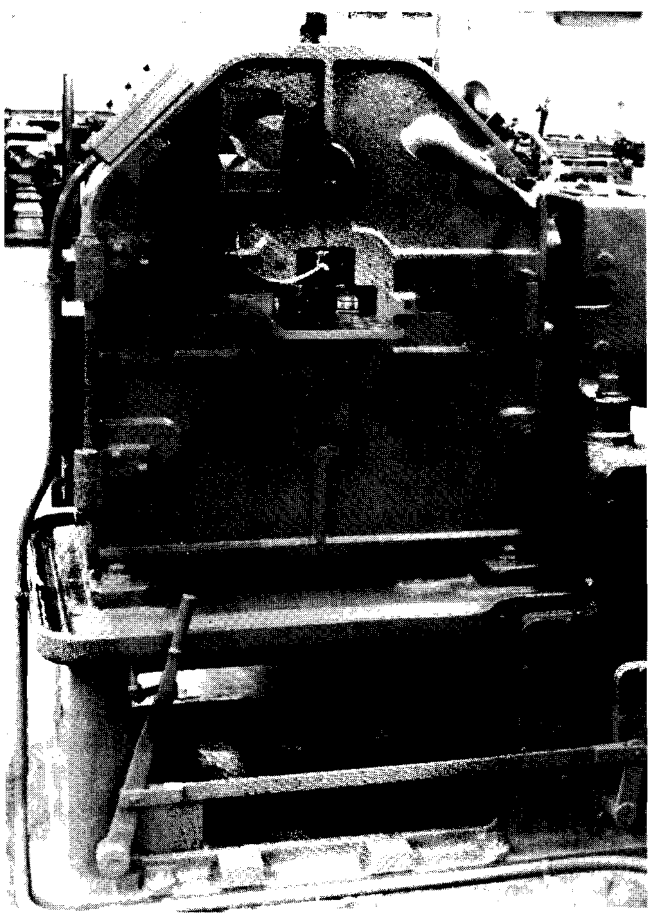


FIGURE 57. POWERED TURK'S-HEAD MACHINE USED FOR SHAPE FABRICATION

Intermediate anneals are usually performed in either a continuous dry-hydrogen-atmosphere furnace or a pit-type retort furnace. A typical conveyor furnace is continuous with a horizontal heating zone 8 feet long followed by a 23-foot cooling zone. Dry-hydrogen atmosphere entering at the end of the heating zone, moves through the heating and cooling zones, maintains dew points below -40 degrees. Belt speed is variable from 2 to 24 inches per minute, and temperatures from 1200 to 2200 F may be attained. In a typical pit-type retort furnace, a vertical retort about 14 feet long is lowered into the electrically heated outer chamber. This furnace can be operated under vacuum with the retort and heating chamber individually evacuated, or the retort may be backfilled with argon, helium, or other inert atmosphere. The heat-treating range varies from room temperature to 2000 F. Form-rolled lengths are hung from a fixture and heat treated in the vertical position.

As a final operation, the lengths are straightened and detwisted on a stretch straightener. In this operation, the lengths are grasped at each end, stretched beyond the elastic limit, and twisted as required to remove twist, camber and bow.

TYPES OF FORM-ROLLED PRODUCTS

Form-rolled products include airfoil configurations, "T", "L", "E", and "V" sections, and a large variety of other shapes whose configuration is amenable to rolling. These shapes vary in size from approximately 1/8 inch in maximum cross section, with edges which are practically knife edge, to 3 inches wide with thickness varying from a few thousandths to over 1 inch. Some representative shapes and materials are shown in Figure 58. The small "V" sections, used for sealing rings, are form rolled from round bar in Inconel 718 alloy. The smaller one is 1/8 inch high, about 0.035 inch through the base. The blade root section, to which compressor rotor blades are welded, is made from AM 350 material. This section has an overall height and width of about 0.150 inch. The channel section is form rolled from a bronze bar (Ampco Metal) for use in a clutch assembly.

The middle row in Figure 58 shows a variety of airfoil sections for a number of applications. The upper airfoil, which is about the smallest presently rolled, is made from turbine-grade Type 403 stainless steel to AMS 5613 specification. The second is rolled from an L-605 cobalt-base alloy material. The third, used in a fluid drive

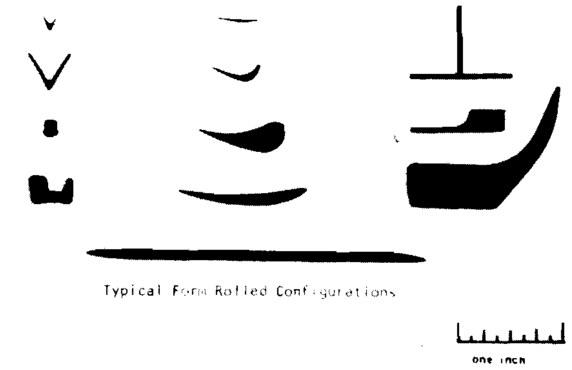


FIGURE 58. TYPICAL FORM ROLLED CONFIGURATIONS

mechanism for earth moving equipment, is rolled in C1018 carbon steel. The fourth is produced in Greek Ascoloy stainless steel. The lower section, about the widest section presently rolled, is about 3.25 inches wide, and varies from 0.095 inch to 0.010 inch. This section is rolled from slit strip in AM 350 material.

The "T" section, in Figure 58, typical of those used in aircraft structurals, is form rolled from round Hastelloy-X bar stock (shown in 10-foot lengths in Figure 59). The stepped section of pure titanium meets AMS 4921 specification and is subsequently formed into a ring used as a support member in a jet engine afterburner. The large hooked section, with a corner to corner width of 1-7/8 inches, maximum thickness of 1/2 inch, and minimum thickness of 0.030 inch at the tip, is produced in Inco 718 material. This section is also formed into a ring used in structural applications.

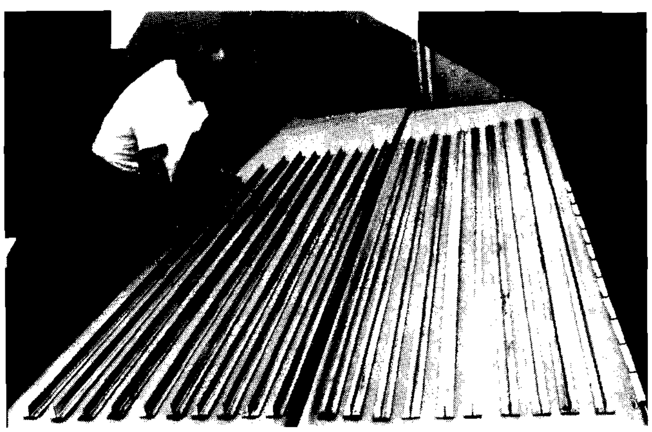


FIGURE 59. HASTELLOY X FORM ROLLED SHAPES

Development work with titanium alloy shapes has been successful. Equipment, tooling and processing techniques have been defined to produce close tolerance net shapes in "T" and airfoil configurations. Finished 10-foot shapes in "T" and airfoil configurations. Finished 10-foot lengths of Ti-8Al-1Mo-1V alloy "T" sections have been produced to the cross-sectional dimensions shown in Figure 60. The processing of titanium alloy materials is considerably different from that of other wrought materials, and special facilities are necessary for production quantities. If large quantities of titanium-alloy structural members become a requirement, the economics for form rolling look very favorable compared with competitive methods.

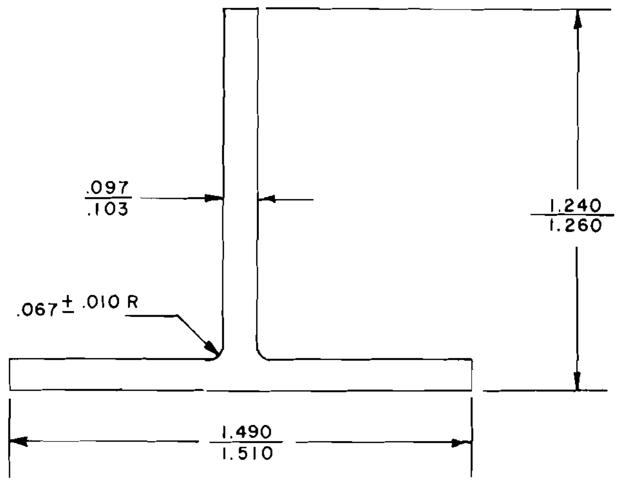


FIGURE 60. DIMENSIONAL CONTROL POSSIBLE IN FORM ROLLED Ti-8Al-1Mo-1V ALLOY SHAPE

PROCESS ECONOMICS

The form-rolling process produces a structural shape essentially to "net" size and shape and no machining is required to improve the dimensional tolerances or surface finish. The metallurgical properties are excellent and likewise require no machining for improvement. Competitive processes include machining and grinding of shapes from bar stock produced by conventional rolling, drawing or extrusion. The initial saving is in the raw material cost. It is estimated that form rolling requires about half the initial weight of bar stock required for extrusion and one-third the weight required for hot rolling to produce the same structural shapes. This represents a considerable saving when the raw material cost is $2.00 to $7.00 a pound and the part is 25 pounds or over in weight. The second saving, even greater, is the elimination of the costly machining to achieve the final shape. Again, it is estimated that over half the cost of a structural shape for aircraft is the machining labor cost. It is reasonable to conclude that the form-rolling process can substantially decrease the cost of a finished part.

The tooling required is usually special and a charge is involved for each configuration. Even slight changes in thickness, height, or width such as in a family of "T" shapes would involve some individual tooling for each part. The tooling charge may vary from $2000 to over $10,000 depending upon configuration, size, and material involved. This is a nonrecurring charge. The cost per foot for the finished shapes can vary from $5.00 to $35.00 depending upon weight, configuration, material, and order size.

The case histories on page 56 show several types of parts that can be form rolled and, in some instances, the cost savings realized over competitive production methods.

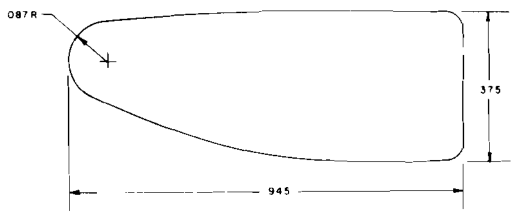
SUMMARY

The form-rolling process as currently applied to the manufacture of structural shapes for the aircraft aerospace industries is a proven process. The product is high quality with essentially "net dimensions" with regard to thickness, shape, surface finish, and metallurgical properties. The cost of initial tooling and price per foot or length of product is usually greater than that for drawn or extruded shapes. The justification and/or economics is the reduction or, in some instances, elimination of the machining often necessary for drawn or extruded shapes.

The processing requires exact control of metal flow and tooling. Slight differences in thickness or changes in height or width of a configuration requires separate tooling. This cost, plus the development time involved, restricts the use of the process with regard to prototype or limited volume quantities. Form rolling is best used for high-volume production after design and material specifications have been established.

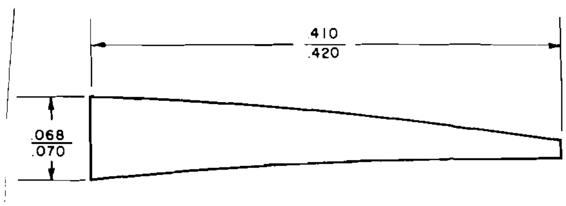
The economical quantity depends on the cost of material, profile configuration, and present machining costs if the part was manufactured as a drawn or extruded shape which required finish machining.

Case History 1



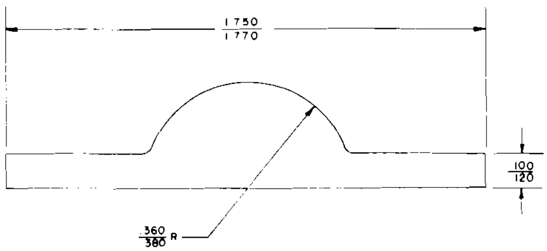
Material – Waspaloy
Tolerance – ± 0.002
Temper – Annealed
End Use – Solid nose pieces for hollow vane
Tooling – $4,500.00
Price per 10 inch piece – $7.00 to $10.00
Previous price – Approximately $5.00 per piece, however, customer scrapped approximately 60 percent of these parts because they could not achieve tolerances and required quality.

Case History 2



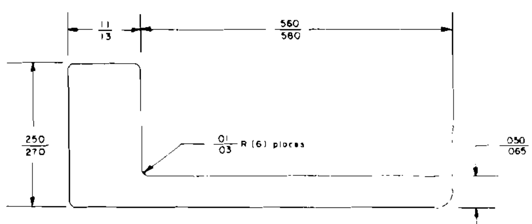
Material – AMS 5613 stainless
Tolerance – ± 0.0015
Temper – Annealed
End use – Stiffener in trailing edge of hollow blade
Tooling – $4,100.00
Price per foot – $1.75 to $2.25
Length – 6 to 12-foot random

Case History 3



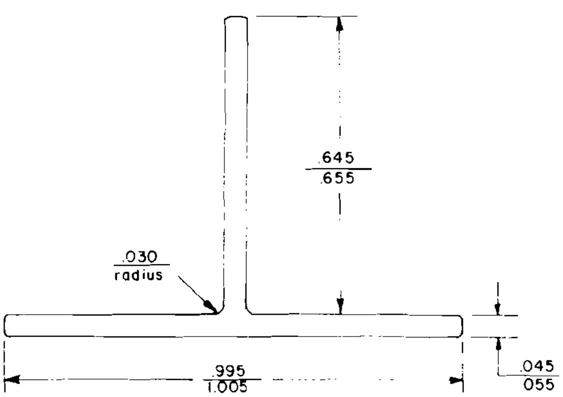
Material – A 286
Tolerance – ± 0.003 Envelope
Temper – As-rolled
End use – Support bar
Tooling – $1,500.00
Price per foot – $7.00 to $10.00
Length – 8 feet and 12 feet
Previous method of manufacturing – machining and grinding
Previous cost per foot – Approximately $17.00

Case History 4



Material – L 605 Cobalt alloy
Tolerance – ± 0.003 envelope
Temper – Annealed
End use – Hinge
Tooling – $6,100.00
Price per foot – $6.00 to $8.00
Length – 6 to 10-foot random
Previous method of manufacturing – machining and grinding
Previous cost per foot – Approximately $11.00
Annual usage – 12,000 feet
Customer paid for tools and saved over $30,000 first year

Case History 5



Radii not indicated to be .020

Material – Hastelloy-X and Inconel 600
Tolerance – ± 0.0025 thickness
Temper – Annealed
End use – Closure member
Tooling – $6,500.00
Price per foot – $7.00 to $12.00 for Hastelloy-X material
$5.00 to $ 9.00 for Inconel 600 material
Length – 10-feet and 12-feet
Previous method of manufacturing – extrusion and machining
Previous cost per foot – Approximately $30.00 for Hastelloy-X and $15.00 for Inconel 600

SECTION 3

MANUFACTURING METHODS FOR DRAWN SHAPES AND TUBING

by

C. S. DuMont
T. G. Byrer

SECTION 3

MANUFACTURING METHODS FOR DRAWN SHAPES AND TUBING

Modern aerospace design is based on the extensive utilization of materials offering high strength-to-weight ratios and availability in a variety of forms such as castings, forgings, sheet, plate, and sections such as T, U, and Z shapes. In addition to the structural forms, extensive quantities of tubing are used in hydraulic power control and fuel circuitry. This section of the report describes manufacturing technology for the production of drawn shapes and tubing. While the procedures used in producing both these product forms utilize the drawing process, they differ sufficiently to merit separate discussions.

DRAWING OF STRUCTURAL SHAPES

Structural sections of high-strength materials used in aircraft construction are currently fabricated by extrusion (see Section 1) followed by machining on all surfaces to obtain required surface finishes and dimensional tolerances. This requirement for machining can be quite extensive and thus costly. For some parts, up to 50 percent of the original volume of the material is removed. This low material yield, together with the cost of machining operations, has prompted extensive research effort into methods for producing extruded shapes to closer dimensional tolerances and thinner sections.

While roll forming of strip can produce a limited geometry in the materials of interest, the extrusion process offers a much broader spectrum of cross sections and shapes and this is of more interest to the aircraft designer. However, the extrusion process had definite limitations regarding minimum thickness of section, usually about 0.090 inches. Since it is desired in many instances to achieve thinner sections on the order of 0.040 inch, attempts have been made to process extruded shapes using special drawing practices. A review of efforts in the drawing of extruded shapes is presented here.

Background

The initial effort on drawing of shapes was sponsored by the Manufacturing Technology Division of the Air Force Materials Laboratory under Contract F33615-1674 with Republic Aviation Corporation (now a Division, Fairchild Hiller Corporation) in 1965[1]. These programs covered the experimental extrusion, drawing, and heat treatment of Ti-6Al-4V and Ti-8Al-1Mo-1V alloys. Drawing was done warm with feed stock preheated to 1350 to 1400 F. Tungsten carbide dies were used at a drawing speed of 10 feet per minute with the dies heated to 400 to 425 F. A combination of conversion coating plus spray coatings plus commercial hot-die lubricant was used. Surface finishes of 100 to 150 microinches, rms (obsolete roughness system), were reported for sections as thin as 0.040 ± 0.005 inch in lengths up to 20 feet.

Subsequent efforts on steel drawn shapes was conducted in a joint program[2] with Northrop Aircraft, H. M. Harper, and Lindberg Steel Treating Company. Materials included AISI 4340, PH-14-8Mo and 18 percent Ni Maraging steel. T-shapes having a 1-inch stem and 2-inch width were extruded and subsequently drawn with an adjustable tungsten carbide die. Concurrent with this effort, the Air Force Materials Laboratory also sponsored programs at Nuclear Metals Incorporated on the back-tension drawing process[3] and at Harvey Aluminum on the development of the convex face draw die[4]. Materials drawn in this latter program included AISI 4340 steel and Ti-6Al-4V alloy. As a result of these AFML-sponsored programs, the development of the convex die, the adjustable die, and the root-shearing die considerably advanced the state of the art and eliminated some of the difficulties frequently encountered in the early work in shape drawing.

These programs have been carried to a point where new concepts appear ready for production applications. Experimental quantities of extruded and drawn shapes have been produced in 20-foot lengths of 2-inch T-sections with 0.040-inch-thick sections in AISI 4340, PH 14-8Mo, 18 percent Ni Maraging steel, and Ti-6Al-4V and Ti-8Al-1Mo-1V alloys. The procedures used in this work are described in the following sections.

Starting Material

The basic starting materials in these development programs for the drawing of shapes were T-section extrusions. Certain inherent conditions in extruded shapes can cause problems in attempts to draw these shapes. Dimensional variations in web and flange thickness along the length of the extrusions can be a source of difficulty in subsequent drawing. In the work on back-tension drawing, the extrusion thickness varied from 0.090-inch to 0.100-inch. In subsequent drawing operations, this variation resulted in reductions in area of from 16 percent to 24

percent within a given length and consequent excessive bowing, bending, and twisting. Although these problems can be corrected in part by subsequent stretching and heat-treatment, the dimensional uniformity of the starting stock exerts a marked effect on the dimensional tolerances obtainable with drawn shapes.

Another important geometric or dimensional consideration is that of the "off-center" vertical leg of a T-section. This type of defect results in subsequent tearing or complete rupture during the drawing operation. In general, as-extruded sections should not vary more than 0.010 to 0.015 inches in major dimensions (i.e., flange and web width and thickness) over the length of the workpiece if drawing with conventional dies is to be accomplished. These tolerances, dependent on the material being processed, are more critical for the titanium alloys than for some high-strength materials and stainless steels. Typical required dimensions for an AISI 4340 extruded steel T-shape to be used in subsequent drawing are shown in Figure 61.

m

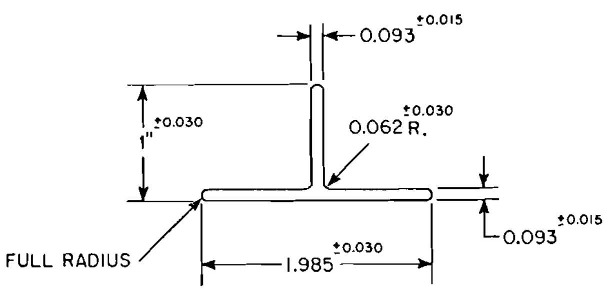


FIGURE 61. REPRESENTATIVE DIMENSIONS FOR AS-EXTRUDED AISI 4340 STEEL SHAPES

Surface finish of 190 microinches, rms. Also a starting requirement for shape drawing.

In all development work to date, the extruded starting material has been of a size which falls within a 5-inch diameter circle. All materials should be in the annealed condition prior to drawing.

The surface of the extruded starting stock should be scale-free and all traces of the extrusion lubricant should be removed. Both grit blasting and etching techniques have been used in the experimental programs on AISI 4340 steel and on the titanium alloys. The drawing operation burnishes the material so that the final drawn forms have a 32 microinches, rms, surface finish, when the starting extrusion has a typical surface finish on the order of 200 microinches, rms.

Equipment

Drawbench

In drawing shapes of difficult-to-work materials, a primary requisite is that of a refined control of the drawbench. In the Northrop program(2), a 50,000-pound-capacity Aetna Standard drawbench was used in conjunction with a 225-horsepower diesel engine. The power coupling included an air-actuated "Power Flow" clutch and a 5-speed transmission. The torque capacity of the clutch was directly proportional to the air pressure available and this system provided a constant force with no dynamic overloading.

For back-tension drawing, as in the Nuclear program, an elaborate load cell-type of control system is utilized.(3) Servocontrol of both forward and back tension in conjunction with 25-ton hydraulic cylinders assures smoothness in applying both loads. As expected, drawing titanium-alloy shapes generally requires greater capacity than drawing steel to equal reductions. The Fairchild work on warm drawing used a 50-ton press equipped with special speed controls.

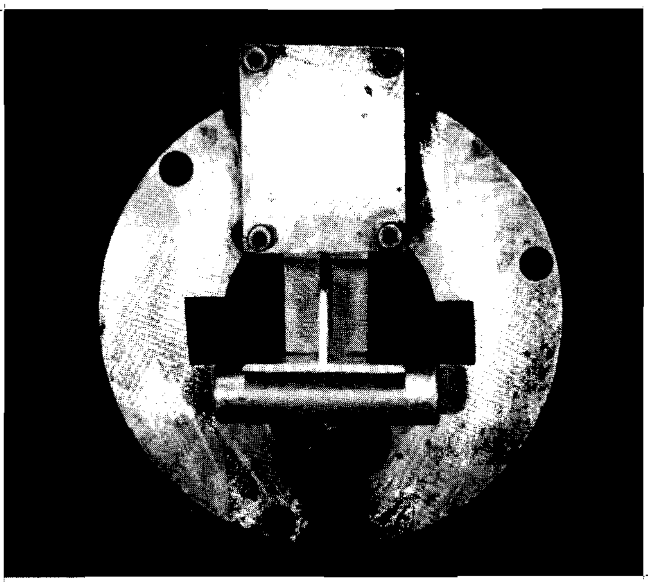
Drawing speed will vary from 2 to 20 feet per minute; 4 to 10 feet per minute presents the optimum trade-off between viable production rates and preferred surface finish. The drawing rate varies with the stage of reduction, and the initial drawing is usually at the lower rates. A minimum run-out length of 20 feet is recommended, 25 feet is preferred.

Another highly important attribute of the drawbench is that of alignment between the die holder, dies, and the clamp carriage. Properly aligned, air-operated, diamond-faced, Hufford grips proved successful in drawing the titanium alloys. The grips must be cleaned properly after each draw to insure complete removal of all traces of scale and lubricant. A roller-shape guide leading to the die entry usually facilitates rapid lead-in for gripping.

Dies

Both carbide and tool-steel dies have been used for drawing steel shapes. For drawing titanium, R-10 carbide dies with a constant approach angle of 16 degrees (half angle) and a constant land length of 0.100 inch were used. Carbide dies are usually preferred for drawing steel shapes as they offer better life and a higher reliability than tool-steel dies.

A second die modification that has improved drawing of T-shapes was used by Harvey to scarf or skive excessive root radii or fillet.[4] In the extrusion process, excessive die wear at the point where the leg meets the base frequently results in the accumulation of excess material at this point. At times, this fillet material was removed by machining or etching, both of which were time-consuming and costly. If this excess material remains, it may result in tearing during the drawing operation, and the debris becomes imbedded in the body of the shape. Also this excess material may cause bowing and distortion during the drawing operation. A cutting die can remove the excess radii and thus simplify the subsequent drawing operation. As the die is designed to match the drawbench die holder, a single pass will serve to size the fillet radii to the desired size. Figure 62 shows the root-cutting tool and a T-shape before and after skiving.



a. View of Tool for removal of fillet material

b. Cross section before and after removal of fillet material

FIGURE 62. REMOVAL OF MATERIAL FROM TEE FILLETS BY CUTTING IN THE DRAWBENCH[4]

Auxiliary

Other equipment required in producing drawn shapes includes heat-treating furnaces and stretch straighteners. Both the as-extruded and the in-process drawn stock will show warpage, twisting, and bending. These conditions seriously interfere with subsequent drawing steps. Stretch straightening at warm temperatures is a necessary intermediate step in processing both steel and titanium sections. Both the AISI 4340 and the PH14-8Mo materials required some form of annealing treatment prior to room-temperature straightening. Resistance heating during stretching was used successfully in straightening titanium when the equipment was controlled adequately to insure the desired tensile levels and increase in length (usually 2 to 3 percent).

Lubrication

Fairchild's lubrication practice for warm drawing of titanium alloy shapes included (1) a proprietary conversion dip coating (Amchem GDL-785), (2) two spray coats of a stabilized dispersion of graphite (MA-235 FUZE-ON), and (3) a hot die lubricant (Fiske 604) applied to the shape immediately prior to entering the die.[1]

In drawing AISI 4340 steel, Nuclear conducted a series of tests on six proprietary commercial lubricants before deciding on Moly-duolube (Hercules Packing Company, Aldon, New York). This selection was on the basis of lower required draw force and the improved surface finish. Northrop preferred to use a graphite-base lubricant in a resin carrier (Fel-Pro C300) for drawing AISI 4340 and the 18 percent Ni Maraging steel. For Northrop, a brush-and-wipe application to a thoroughly dry extrusion surface permitted three passes through the drawing die with one application. Further, the initial 100 microinch, rms, surface was improved to 16 microinches, rms, after three passes. This coating also provided adequate protection against any atmospheric corrosion during storage of the drawn extrusions. While the lubricant cannot be removed by chemical methods, it is easily removed by a light grit blast. For drawing the PH14-8Mo extrusions, a Bonderite 70 plus Teflon or soap lubrication was adequate. Again, it was emphasized that the surfaces of the extrusions should be free of all traces of moisture before the lubricant is applied.

Pointing

A most-troublesome aspect of a drawing operation is that of pointing or reducing the cross section of a short length of one end of the part to be drawn so that a sufficient length can be inserted through the die to permit engagement within the grips. Both the swaging of round stock and acid etching of irregular shapes are standard practice in the drawing industry. Each of these procedures results in frequent breakage and loss of material due to cropping the pointed ends. Breakage becomes more frequent in shape drawing as the shape thickness decreases.

The development of an adjustable die has eliminated the pointing problem. The details of this die, developed by Northrop, are shown in Figure 63. The die and diecase arrangement is such that tapered wedges force the die segments onto the extrusion surfaces by turning four bolts. Figure 63 is a detail drawing of the adjustable draw die case, dies, and inserts. The procedures in using the adjustable draw die are (1) open the draw-die case and loosen the adjusting bolts, (2) insert the extrusion, (3) close the die case with the cover plate, (4) grip the extrusion with the gripper head and pretighten the die adjusting bolts, (5) draw about 4 inches of extrusion through the die, (6) stop the draw and adjust the bolts to the desired thickness, and (7) draw the extrusion. A similar approach was used by Nuclear Metals in their back-tension drawing studies. For this work, an adjustable T-drawing die was purchased from Extrude-All Die and Engineering Company, Warren, Michigan.

SHAPE DRAWING WITH A CONVEX DIE

Excessive variations in the thickness of the as-extruded starting stock can cause buckling, twisting, tearing, edge cracking or fracture during a standard drawing operation. In the normal drawing process, reduction of thickness of the section results only in an increase in section length. Thus, in drawing shapes through conventional dies the flow of metal is basically longitudinal, and any variation in thickness in the respective sections of the starting shape will result in nonuniform flow. The result is occurrence of one or more of the above-mentioned problems.

In an effort to correct or eliminate these difficulties, an AFML-conceived die design denoted as a "convex die" was examined in several Air Force-funded programs[3-7]. The convex die allows both lateral and longitudinal distribution of the metal during the drawing operation. Figure 64 shows a conventional draw die and the convex-die design. Figure 65 shows how a shape cross section changes when drawn with a conventional and convex draw die. The lateral distribution of metal accomplished with the convex die has proven to be effective in reducing distortion and tearing and has broadened the acceptable tolerances of the starting stock dimensions that can be successfully drawn. Several alloys including AISI 4340 steel, Ti-6Al-4V and Beta III titanium alloys, and 6063 and 7075 aluminum alloys have been cold and/or warm drawn successfully. Shapes drawn with a convex die develop surface finishes superior to those obtainable with conventional shape drawing methods.

The initial effort in developing the convex draw die was conducted by Harvey Aluminum[4] (now Martin Marietta Aluminum). In the early stages of development it was reasoned that fabrication of solid, or one piece, convex face dies for drawing tee shapes would require intricate machining and an extensive number of dies. Further, pointing or reducing ends for gripping the length to be drawn would require undue effort and expense as well as contribute to frequent breakage. Thus, efforts were directed toward designing a three-piece die system as shown in Figure 66. This design also allowed the die to be opened to admit the leading end to be gripped by the draw-head jaws. Further, shims or threaded adjustments of the respective segments would allow a wider range of starting thicknesses and increments of reduction not obtainable with a one-piece die.

As mentioned earlier, material flow in conventional dies is longitudinal; the convex die results in some lateral flow of the material during the drawing operation. By varying the included angle of the die, the degree or extent of the lateral flow can be controlled. The proportion of lateral movement for the various included angles are as follows:

Included Die Angle, degrees	Approximate Percent Lateral Movement
60	50
90	25
135	10

The ability to control the proportion of lateral movement may be used to advantage in reducing the effects of thickness of the starting stock during the initial drawing stages. In drawing AISI 4340 steel tees from 0.093 to 0.040 inch, a 60-degree die would be used for the first two passes to eliminate any thickness variations, after which the remaining reductions would be done with a 135-degree die to maximize shape lengthening. In cold drawing AISI 4340, it is possible to obtain reductions of 20 percent per pass with standard surface preparation techniques and commercial lubricants. Except for the die holder and grips, conventional hydraulic drawbenches of

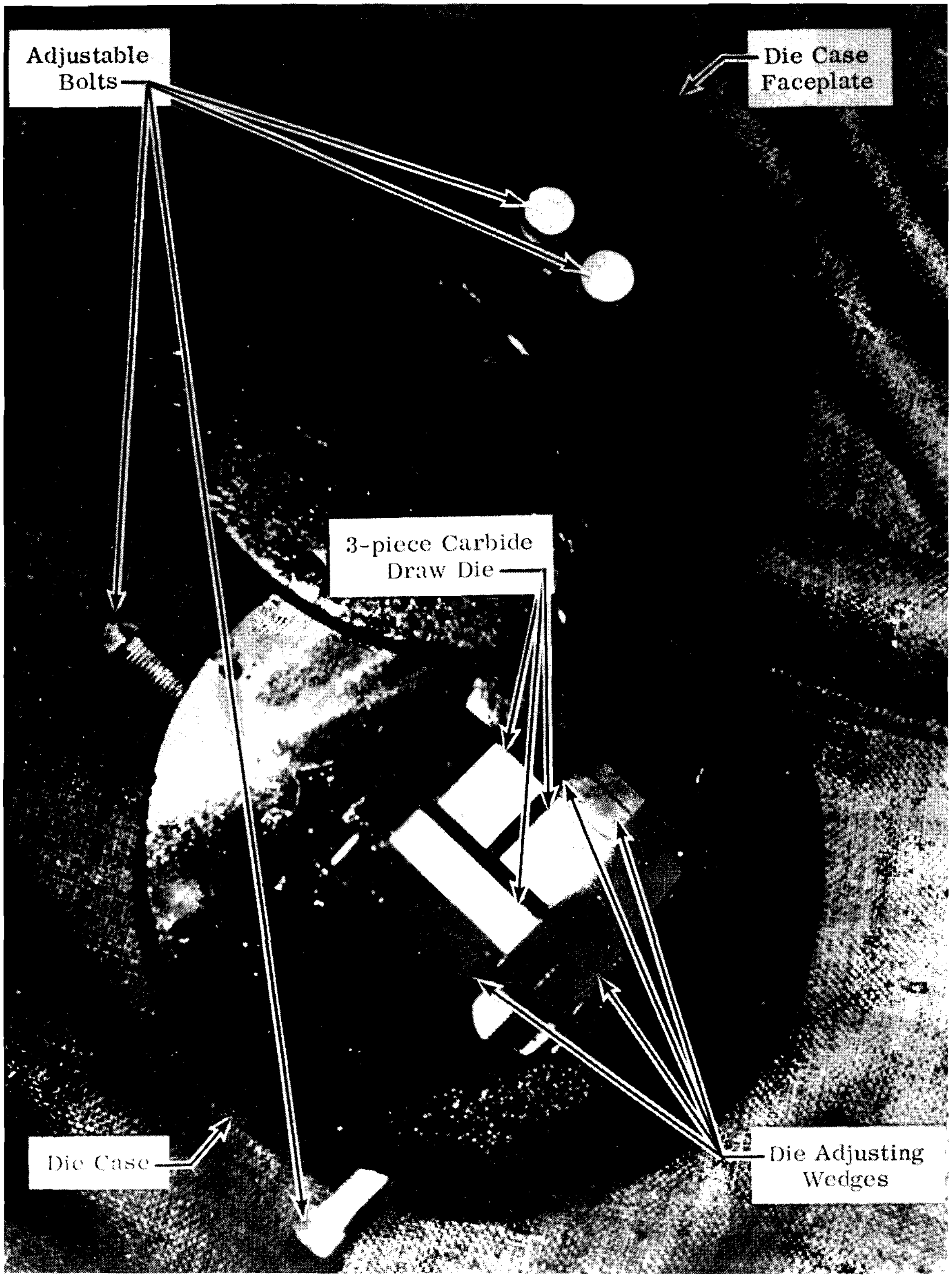


FIGURE 63. PHOTOGRAPH OF ADJUSTABLE DRAW DIE THAT ELIMINATES THE COSTLY AND TIME CONSUMING "POINTING" OPERATION

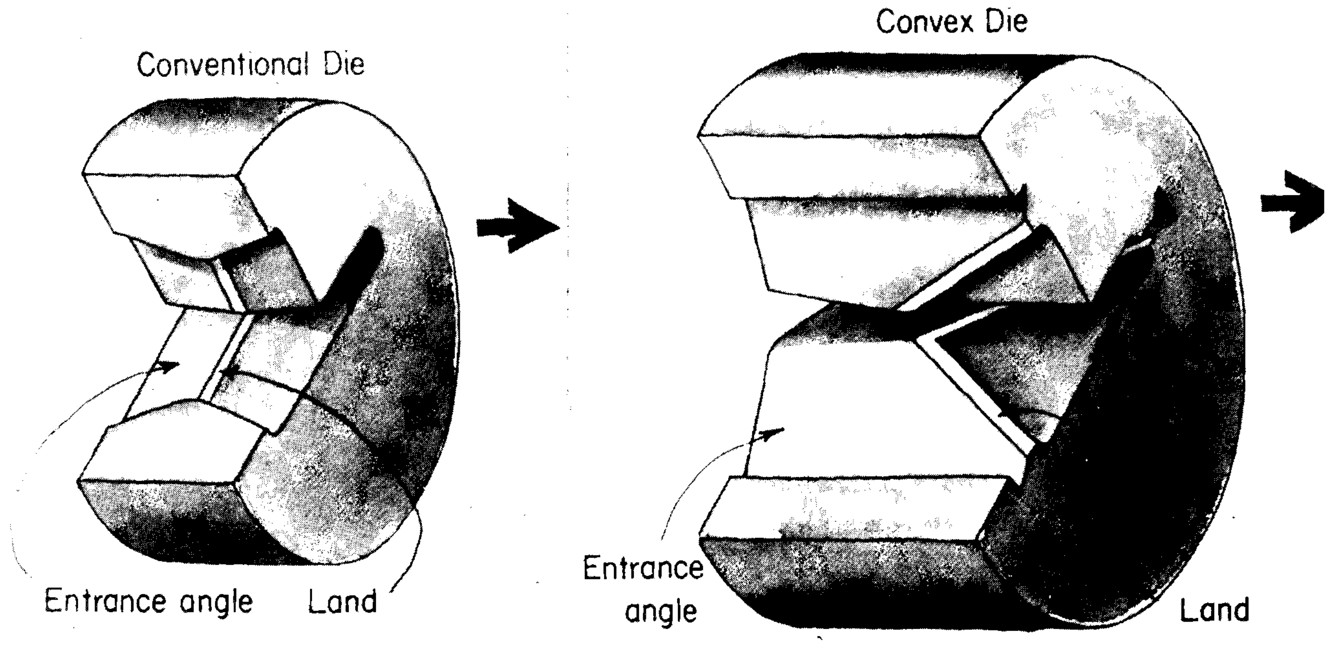


FIGURE 64. COMPARISON OF CONVENTIONAL DRAW DIE WITH CONVEX DIE SHOWING DIFFERENCES IN DIE LAND DESIGN[5]

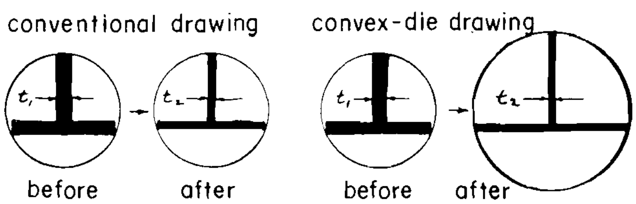


FIGURE 65. CHANGES IN CROSS SECTION OF TEE SECTION DRAWN WITH CONVENTIONAL AND CONVEX DRAW DIES[8]

50,000 pound capacity can be used. However, control of the drawing speed is important and should be continuously variable to produce a range of 0 to 20 feet per minute. A typical drawbench set-up for convex die drawing is shown in Figure 67.

As might be expected, the extent of lateral flow obtained with various die angles will have a pronounced effect on the drawing force required and on the resultant distortion contributed by dimensional variations in the starting material. These factors were investigated by Harvey Aluminum[4] who reported the following data for experimental 6063 aluminum-alloy drawn shapes:

Included Angle, degrees	Draw Force, pounds: 15 Percent Reduction	Draw Force, pounds: 20 Percent Reduction
135	2500	3000
90	3000	3750
60	3750	5250

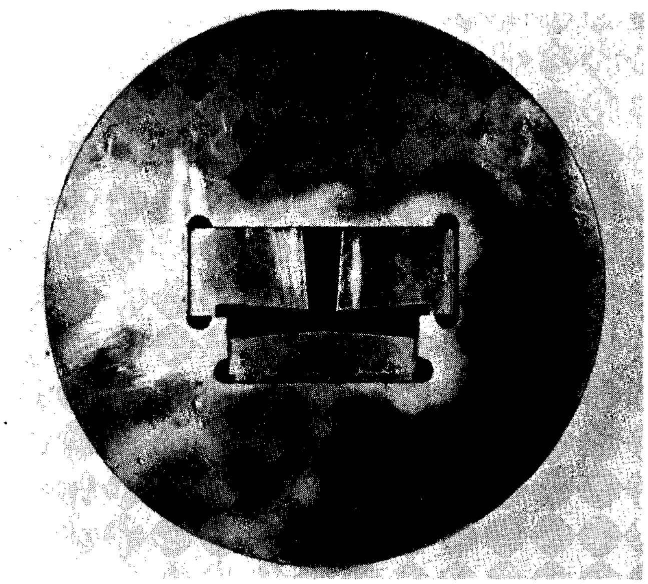
Drawing forces of the magnitude encountered with the smaller included die angle suggest that in drawing thin sections, breakage in the grips could be a problem that requires a stronger grip end on the tee to be drawn. It is to be noted that similar relationships between die angle and draw force were found in drawing titanium and steel.

In work to determine the effect of die angle on shape distortion, it was found that the 60-degree die angle reduced the distortion to the most acceptable level as seen in Figure 68.

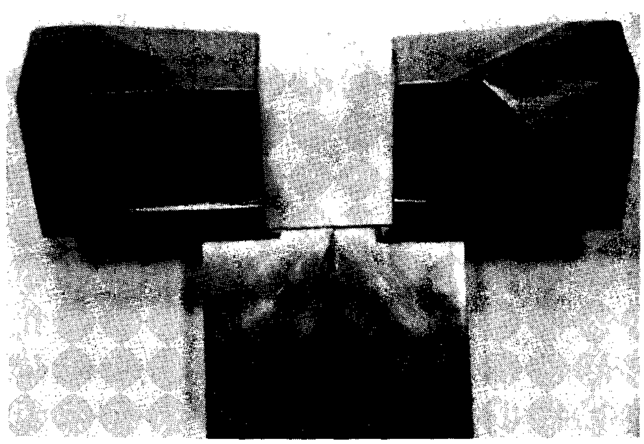
Drawing practices are determined to a considerable extent by the material being drawn. In drawing annealed 7075 aluminum, reductions in thickness of up to 30 percent can be achieved in a single pass, but 35 percent reductions per pass may show evidence of tearing. Total

reductions in thickness from 30 to 50 percent between anneals are possible with zinc phosphate and soap lubricants. Total reductions of this magnitude will reduce the root radius from 1/8-inch fillet in the initial material to 1/16-inch fillet in the final shape. The lateral movement of material provided by the convex die also results in marked improvement in surface finish. An initial finish of 35 microinches, rms, on a drawn shape will improve to about 20 microinches, rms, in the final shape.

In drawing AISI 4340, reductions of 20 percent per draw have been reported at the higher thicknesses with production rates of 10 feet per minute. Five draws with intermediate anneals were required to reduce the thickness from 0.093 inch to 0.040 ± 0.002 inch and an initial surface finish of 190 microinch, rms, was improved to 32 microinch, rms. The mechanical properties of both annealed and heat-treated* AISI 4340 steel drawn shapes indicated an appreciable increase in yield strength but with some decrease in ultimate strength as compared with as-extruded properties. However, these data were based on limited experimental effort and further efforts are needed to verify them.



a. Inserts and shims assembled in casing



b. Three-piece die inserts

FIGURE 66. CONVEX FACE DRAW DIE – 90-DEGREE INCLUDED ANGLE[4]

PRODUCTION POTENTIAL FOR DRAWING SHAPES

While the development efforts described indicate considerable success in establishing drawing techniques for a variety of simple shapes, they have seen little or no use in the production of "net dimension" shapes for aircraft construction. For future reference, however, a cost comparison has been made as part of this program to assess the relative cost of overall machining extrusions to obtain the desired finished dimensions, and that for finish drawing of an extruded shapes.

In the discussion below, data generated for warm drawing by Fairchild[1] are used and updated for use of the convex draw die, since this technique appears most practical for the warm drawing of shapes. Considering the cost of extrusion first, the Fairchild work showed a cost of $11.64/foot for extruding 0.063-inch-thick T-sections in lots of 125 billets. The authors have revised these data to $6.54/foot assuming certain modifications in these costs are practical in an optimized production situation. The basis for both these calculations are shown in Columns 1 and 2 in Table 16. A further cost reduction is proposed in Table 16, Column 3.

Part of the cost reduction suggested here is based on a reduction in die cost due to the less stringent requirements on dimensional tolerances of the extruded shapes, since these shapes would be subsequently drawn with the convex die which can accommodate greater thickness variations than the conventional draw die used in the Fairchild work. This means that more pushes per die can be realized, thus, lowering the die cost. Thus, it is suggested in Table 16 that on a straight comparison with the Fairchild data utilizing cost figures in effect at the time that report was written, it is reasonable to assume that an extruded section can be produced at a cost of about $4.60 per foot.

Moving on then to the comparison in Table 17, projected costs are shown for use of the convex draw die for processing this lot of 125 extrusions. Again, in comparison with the data presented in the Fairchild report for drawing with conventional dies, drawing costs are reduced

*1550 F for 15 minutes; oil quench; 850 F for 4 hours plus air cool.

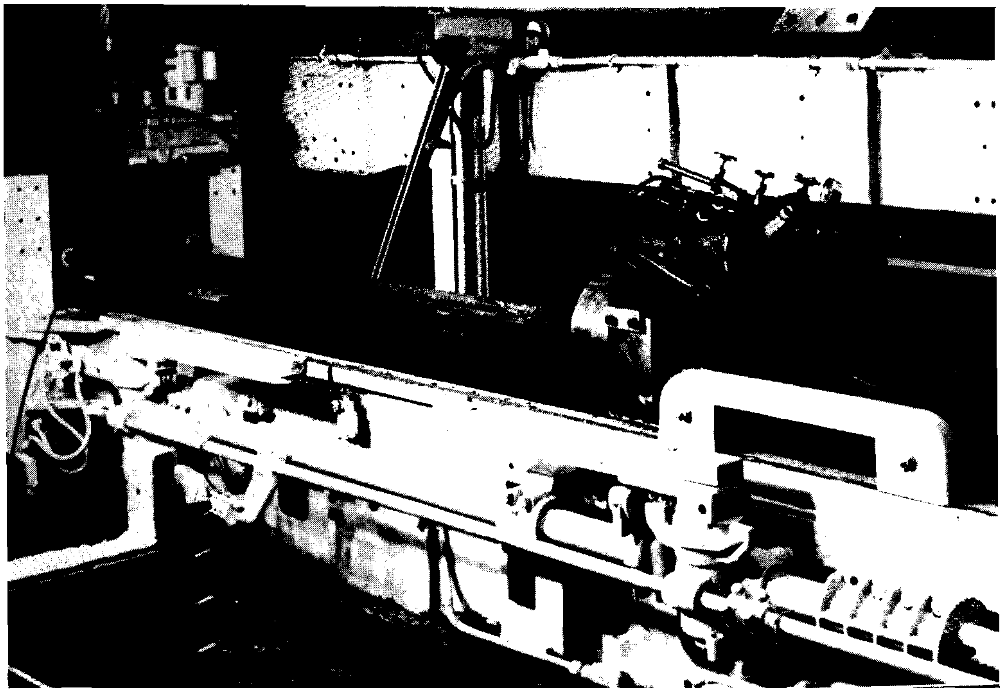
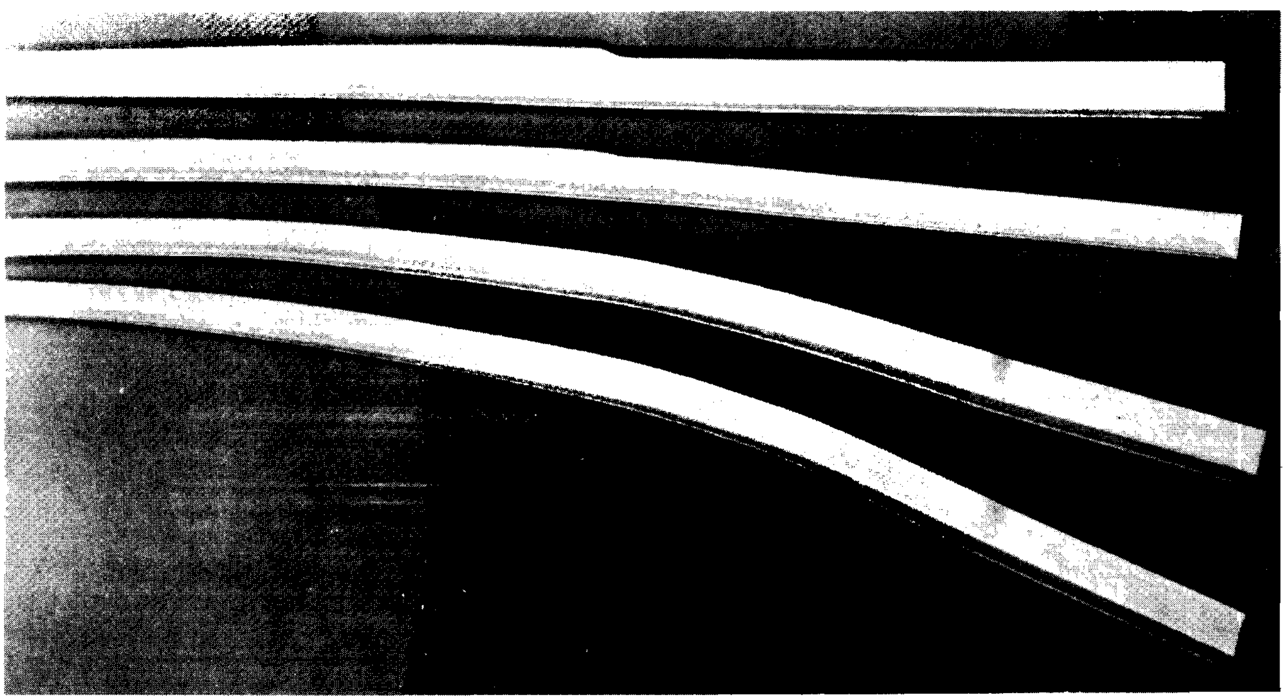


FIGURE 67. WARM DRAWING SETUP FOR DRAWING TITANIUM SHAPES WITH CONVEX DIES[6]



View of 5-foot length after drawing to obtain uniform thickness using dies with included angles as shown (from top to bottom): 60, 90, 135 and 180 degrees (straight).

FIGURE 68. EFFECT OF CONVEX DIE INCLUDED ANGLE ON FLATNESS OF TEES WITH STEM 0.010-INCH THICKER THAN BASE[6]

TABLE 16. COST ANALYSIS – EXTRUSION OF Ti-6Al-4V ALLOY SHAPES

Operation	Cost Per Foot of Extruded Shape--2000 Foot Run of 125 Billets, dollars: Original Fairchild Data(1)	Revised for Production Setup	Revised for Subsequent Convex Die Drawing
Material--billet cost of \$3/lb--80 percent yield from a 3-1/2-inch diameter x 7-inch-long billet	1.80	1.80	1.80
Billet Machining--\$8/billet	0.50	0.50	0.50
Spray Coating of Billets--spraying of 60 billets per hour at cost of \$10/hour	0.01	0.01	0.01
Dies--precision coating plus machining, coating, and grinding--3 pushes per die at total cost of \$93 including recoating for second and third pushes	5.83	3.00(a)	1.08(b)
Die Lubrication--glass pads and glass wool	0.25	0.05(c)	0.05(c)
Extrusion--based on 15 pushes per 8 hour shift--cost of \$300 per hour for press, crew, and furnace	3.00	0.93(c)	0.93(d)
Descale, Etch, and Inspect	0.25	0.25	0.25
Total Cost/Foot of Extrusion	\$11.64	\$6.54	\$4.62

(a) Production setup should reduce these costs by at least 50 percent.
(b) Based on potential cost of \$32 per die + \$10 for reconditioning and recoating between pushes; 3 pushes per die. Cost reduction reflects relaxed need for precision in the extrusion die.
(c) Costs should not exceed \$0.80 per push.
(d) Revised to reflect 20 pushes per hour at cost of \$300 per hour.

TABLE 17. COMPARATIVE COSTS FOR DRAWING Ti-6Al-4V ALLOY-CONVENTIONAL VERSUS CONVEX DIE FOR 125 EXTRUSIONS

Operation(a)	Cost Per Foot During Drawing, dollars: Conventional Die Drawing(a)	Convex Die Drawing
Pointing--use of push pointer with preheated tip	0.025	--
Cleaning--HNO_3/HF batch pickle	0.05	0.05
Lubrication--application of conversion coating plus sprayed graphite coating plus Fiske 604 on die	0.21	0.21
Dies--assumes cost of \$1500 using tungsten carbide dies for 4 draw passes on 125 extrusions	0.19	0.08(b)
Drawing--20 draw passes per hour and 3-man crew at \$70 per hour	0.175	0.15(c)
Straighten--6 shapes per hour with 2-man crew at \$35/hour	0.35	--
Descale, Etch, and Inspect	0.20	0.20
	\$1.20	\$0.20
For 4 passes per extrusion, cost equals 1.20 x 4 = \$4.80/ft of finish drawn shape	For 3 passes per extrusion, cost equals 0.69 x 3 = \$2.07/ft of finish drawn shape	

(a) Conditions listed for each operation are based on Fairchild estimates.
(b) Use of cast steel die segments which are heat treated and ground should cost approximately \$500 plus \$200 allowance for reconditioning--use die life estimated at 10,000 feet of shape.
(c) Slight cost decrease reflects less downtime due to problems during drawing with the convex die.

by more than 50 percent by utilizing the convex draw die. The difference here represents (1) eliminating the requirements for pointing since the convex draw die is adjustable, (2) reduced costs in manufacture of dies, and (3) eliminating the requirements for straightening of the shapes between draw passes.

The data from Tables 16 and 17 are compared in Table 18 with the cost of machining the extruded shape as is presently done in industry. As estimates of the cost of machining extrusions vary considerably, they are indicated here to range from \$5 to \$10 per foot based on 1970 cost estimates which would be comparable to the cost factors used in the Fairchild report.

TABLE 18. COST COMPARISON OF MACHINING AND DRAWING EXTRUDED SHAPES

Overall Machining of Extruded Shape		Convex Die Drawing of Extruded Shape	
Extrusion, cost/foot	1.0	Extrusion, cost/foot	1.0
Machining	1.1 to 2.1	Convex die draw cost/foot	0.45
TOTAL	2.1 to 3.1		1.45

Rather than updating these costs to 1973 levels, Table 18, showing a simple ratio of comparisons with the cost of the extruded shape on a per foot basis equal to unity, indicates that convex-die drawing of shapes should reduce present costs of a net extrusion by 30 to 50 percent. These conditions are, of course, predicated on the basis of the manufacture of sizable quantities of a single shape configuration in high-strength titanium alloys. Under these conditions convex-die drawing of extruded shapes should have definitive cost advantages over present techniques of overall surface machining of an extrusion.

FABRICATION OF SMALL-DIAMETER TUBING

The aerospace industry requires premium-quality tubing which, in addition to having a high strength-to-weight ratio, must offer fabricability and corrosion resistance in a wide range of environments. While size requirements range from hypodermic needle size to 8 and 10-inch diameter ducting at 0.012 to 0.065-inch wall thickness, most critical sizes for aircraft construction are 1/4 to 1/2 inch in diameter with 0.020 to 0.050-inch wall thickness. The most common applications for these tubing sizes are:

Hydraulic systems lines
Cryogenic fluid transport
Fuel system plumbing
Environmental-control ducting
Tubular structural members.

For these applications, the primary materials of interest are the titanium alloys, although some steel tubing is used. Other aerospace and nuclear-power applications have prompted research effort on processing TD-nickel chromium and alloys of tungsten, tantalum, columbium, and cobalt. These materials all require careful control of all processing procedures and many are difficult to fabricate in tubular form. Tubes of these metals are expensive and their cost has prompted a number of research programs directed to improving production processes for tubing manufacture.

An additional incentive for government sponsorship of process-development programs is that tubing manufacture is considered highly proprietary and data are sparse in the technical literature. For example, the seven volume ASM Handbook is essentially void of information on tube-fabrication practices.

Background

All tubular products are generally classified by manufacturing processes, namely: seamless and welded grades. In addition, the intended application presents two further categories: mechanical and pressure tubing. The discussions here deal only with seamless tubing intended for pressure applications.

Seamless tubing has been preferred traditionally for aircraft applications requiring optimum reliability. However, seamless tubing is usually not uniform in wall thickness and concentricity, and it is more costly to produce than are the welded grades. This latter consideration, together with the marked improvements in welding technology, have prompted extensive research and development programs directed toward improving the quality and reliability of welded tubing for aircraft applications. However, seamless tubing continues to be specified almost exclusively for aircraft applications, solely on the basis of quality and reliability.

Tube Manufacture

Contemporary literature cited in the bibliography and references frequently mentions that, irrespective of the alloy compositions or process procedures used, the quality of finish tubing produced depends basically upon the freedom from external and internal defects in the starting material. Surface quality and concentricity, grain size, and freedom from inclusions and porosity are important factors. Because of the importance of starting material quality, practices for producing tube blanks are reviewed briefly.

The production of seamless tubing begins with a forged or hot-rolled solid billet. Recent attempts to produce hollow starting cylinders or billets by centrifugal casting or by powder methods have not attained commercial acceptance. For mechanical tube making of ferrous products, solid billets are hot pierced and mechanically hot worked by a variety of tube-forming methods to produce a tube. In each of these processes, the procedure consists of three basic operations

- Piercing a solid billet to form a tube shell
- Elongating the shell with the bore supported by a solid mandrel or plug
- Subsequently elongating the tube with the unsupported bore.

These techniques are used for mechanical tube manufacture of tube sizes down to about 1-inch diameter. Smaller sizes are then made by subsequent cold-drawing operations.

For seamless tubes of the more exotic or hard-to-work alloys, a tube blank is extruded to produce a tube shell for subsequent working by drawing or tube reducing to the small sizes indicated earlier. Tube reducing and drawing techniques are described in more detail below.

Tube Reducing

Tube reducing or rocking is a cold, mechanical, incremental roll-forging technique. This cold rocking process permits reductions of up to 50 percent between anneals, produces smooth surfaces, and improves concentricity. In this process, the tubing is rolled down over a tapered mandrel by semicircular dies with tapering grooves. These dies, as shown in Figure 69, are mounted concentric and do not rotate but rock back and forth, thus the name rocking. The mandrel and tube are rotated between strokes and move forward at the same time. While the

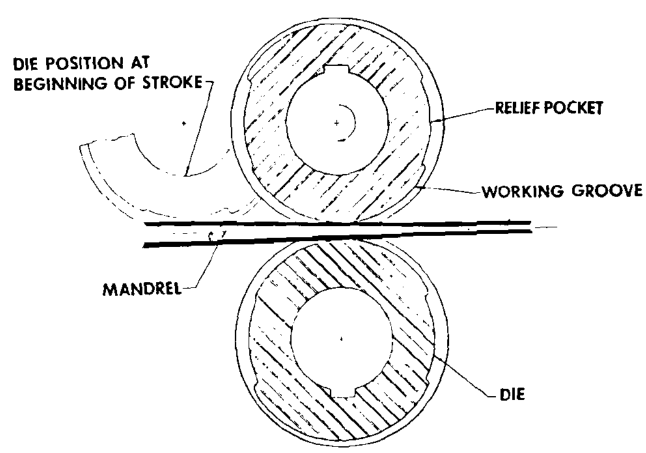


FIGURE 69. DIE, MANDREL, AND TUBE RELATIONSHIP DURING TUBE REDUCING

production rates are low (0.010 to 0.060 inch/stroke at 150 strokes per minute) compared to those for other forming processes, "rocking" is widely used as a process intermediate between the extruded blank and the final drawing operation or as a tube-finishing process for many materials.

While the tube reducing method is slow and can be only a cold-working operation, it has the advantage over drawing of being able to work materials which have inherently low ductility. Whereas in drawing where the tube is under tensile stresses due to pulling the tube through the die, tube reducing generally exerts compressive forces on the tube as it is rotated and rocked through the forming dies. For this reason many of the more difficult-to-work materials, particularly the Ti-6Al-4V alloy, have been processed to the small tube sizes of interest in the aircraft industry by tube-reducing methods. An extensive program conducted by Wolverine Tube Division[9], Universal Oil Products Company, established tube-blank and tube-reducing methods for fabricating this alloy in tube sizes down to 0.375-inch OD x 0.020-inch-wall thickness.

Although this program defined processing conditions for the manufacture of Ti-6Al-4V tubing, subsequent attempts to use this material in a number of advanced systems have not proven economical. The low ductility of the titanium alloy and the extreme care necessary in preparing both OD and ID surfaces for tube reducing still result in considerable scrap loss during processing. Also required is complete chemical milling of the tube ID after the final processing steps. In addition, attempts by McDonnell-Douglas[10] to develop flaring and bending procedures for this alloy were generally unsuccessful.

Therefore, the only titanium alloy used in current aircraft applications is the Ti-3Al-2.5V alloy. It is processed by the same route as its higher strength counterpart. However, this material is reported to require chemical milling of the ID surface before use.

A new, more ductile titanium alloy having the composition Ti-3Al-8V-6Cr-4Mo-4Zr has been fabricated by Reactive Metals[11] to tube sizes of 0.375-inch OD x 0.025-inch wall by the cold tube-reducing process. As shown in Figure 30, this alloy has exceptionally good fabricability and is readily bent and flared as required in aircraft fabrication. Other tubular products processed by tube reducing of an extruded tube hollow include T-111 (Ta-8W-2Hf) tubing fabricated on a program by Westinghouse Astro Nuclear Laboratory[12] and columbium alloy, D-43, fabricated on a program conducted by E. I. duPont Company[13]. The tantalum-alloy tubing was of fairly large diameter (3- to 4-inch OD) and was fabricated both from seamless and welded starting billet stock. The columbium D-43 was fabricated to 0.250-inch OD x 0.020-inch wall.

A recent development in the area of tube reducing involves a new design of equipment designated as "HPTR" cold tube reducers. These mills utilize the "Sendzimir" principal which uses multirollers for cold rolling thin sheet. With the HPTR design, a series of rolls, circumferentially positioned around the tube, roll against the tube surface through a cam arrangement with the frame of the unit. Thus, this design differs from the conventional tube-reducing design in that it utilizes multiple rolls moved against the tube surface by the cam arrangement rather than the tapered grooves in the roll surface as in conventional tube reducers.

There is interest in this type of equipment for fabricating thin wall tubing in diameters as small as 0.25 inch with wall thicknesses as low as 0.003 inch. Designs are also available utilizing these machines for making finned and shaped tubing. These tube reducer mills were developed in the Soviet Union and are now being marketed worldwide by Patent Metallurgical Systems, Incorporated, Raleigh, North Carolina. Several units are operating in the United States and these tube-reducing mills are expected to find wider applications in making very small size tubing.

Tube Drawing

Tube drawing over a mandrel is, of course, an old process for making small-diameter, thin-wall tubing. Its advantages are those of relatively high production rates particularly in comparison with tube reducing and added capability to be drawn at cryogenic or highly elevated temperatures as well as room temperature. As indicated earlier, however, the principal problem with the drawing of low-ductility materials is the tensile stress the tube must undergo during drawing. This encourages point breakage and tube breakage particularly at small sizes. Use of warm temperatures, of course, can alleviate this problem somewhat, but the general trend has been to use the less severe tube-reducing process for low-ductility materials.

A program conducted by Fansteel developed techniques for the manufacture of TD-nickel chromium tubing[14]. A comparison of warm-drawing and cold-drawing techniques for this alloy show that the latter approach was most desirable incorporating intermediate anneals for the manufacture of this alloy in tube sizes down to 0.156-inch OD x 0.020-inch wall. Recent literature indicates that seamless cobalt-alloy tubing is being manufactured by Zirconium Technology Corporation, Albany, Oregon, for use in the space-shuttle fuel system[15]. Presumably, this material will be fabricated by drawing techniques. Ta-10W and Ta-222 (Ta-9.6W-2.4Hf-0.1C) tantalum alloys were successfully fabricated

by Allegheny Ludlum Steel Corporation[16] to tube sizes of 0.250-inch OD x 0.020-inch wall combining both tube-reducing and tube-drawing methods.

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SECTION 4

COMPETITIVE PROCESSES

by

F. W. Boulger

SECTION 4

COMPETITIVE PROCESSES

INTRODUCTION

Several processes are or may become economical alternatives to the extrusion approach to producing aircraft structural shapes and tubing. Some are in various stages of development, and thus currently suffer from various disadvantages. If the developments are successful, however, the processes may find use for certain types of materials and products. In addition, several well-established fabrication processes compete to some extent with the production of structural shapes by conventional extrusion. The following sections describe the potential advantages and probable limitations of several of these alternative processes.

BRAKE BENDING

Flat sheets can be formed into structural sections such as angles, channels, and hats by bending. The brake-forming process uses simple, inexpensive tooling versatile enough to be quickly adapted to producing different shapes. Two typical brake-forming setups are shown in Figure 70. In air bending, the work is supported only at its outer edges so the length of the stroke determines the bend angle α of the part. The punch radius controls the inside radius of the product. In die bending, the sheet is forced into a cavity controlling the part angle. The limiting span width (S in Figure 70a) depends on the punch radius, R, and the sheet thickness, T. According to Wood[1] the practical limits for brake bending lie between:

$$S = 2R + 2T \text{ and } S = 2.1R + 2T \quad .$$

Those variables, the bend angle and the properties of the workpiece material, control the success or failure in bending. Larger radii are necessary for thicker sheet, for bends parallel to the rolling direction, and for less ductile materials; the ratio of R/T should also be increased for larger bend angles. If the operation is too severe, the metal cracks on the outer surface of the bend. Brake forming is used mainly for making parts with wide tolerances or for preforming operations on close-tolerance parts. A typical tolerance for dimensions resulting from brake forming is ±0.016 inch for materials with thicknesses up to 0.125 inch. Hand-working or hot-forming methods are required for achieving close tolerances.

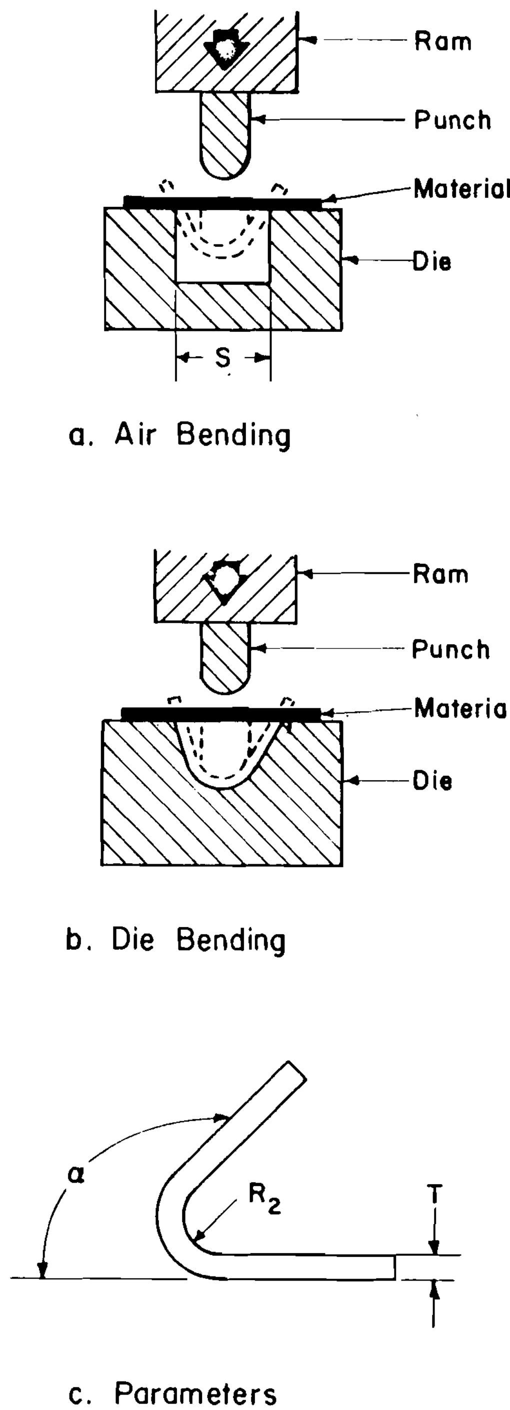


FIGURE 70. TYPICAL BRAKE-FORMING SETUPS AND PARAMETERS

Brake forming is conducted on presses. Depending on the load capacity they can be manually, mechanically, or hydraulically driven. The load capacity and the bed length of a brake press limits its applications. Typically, brake presses have capacities from 5 to 1500 tons and bed lengths ranging from 2 to 24 feet. The bed length limits the length of parts that can be produced on the press.

Wood showed that the limiting strain before fracture depends on the following relationship[1]

$$E = \ln \sqrt{1 + T/R} \ ,$$

where E = logarithmic or natural strain

T = sheet thickness

R = bend radius.

He also showed that the strain in a tensile specimen with a 0.25-inch gage length, corrected for width strain, gives a good indication of the performance to be expected from a particular workpiece material. Since data for such a small gage length are often not available, limiting bend radii for forming operations are usually estimated from experience. Such values are given for several alloys in Table 19. Data of that kind are also used for predicting forming limits in other types of operations.

TABLE 19. MINIMUM BEND RADII FOR PRESS-BRAKE FORMING OF SHEETS WITH THICKNESSES UP TO 0.070 INCH

	Minimum Bend Radii (R/T) for Temperatures Indicated(a)			
	70 F	400 F	600 F	800 F
Heat Resistant Alloys				
A286	0.4	--	--	--
Inconel X-750	0.4	--	--	--
Hastelloy X	0.8	--	--	--
J1570	1.6	--	--	--
Refractory Metals				
Mo-0.5 Ti(b)	16	4	--	8
Tungsten	--	--	5	--
Titanium				
Commercially pure	3	--	--	--
Ti-8Mn	4	2.5	--	4
Ti-6Al-4V(c)	4.5	4.3	--	3.5
Ti-8Al-1Mo-1V	4.3	--	--	2.5
Aluminum				
1100-0	0	--	--	--
1100-H16	1	--	--	--
1100-H18	2	--	--	--
6061-0	0	--	--	--
6061-T6	2	--	--	--
7075-0	1	--	--	--
7075-T6	6	--	--	--

(a) Bend radius, R; sheet thickness, T. Data for 90-degree bends on annealed materials.
(b) Data for 0.012 to 0.050-inch-thick sheet bent to 120-degree angle.
(c) Minimum bend radii range near 2t at 1100 F and 1t at 1500 F.

Parts producible by brake forming can often be made in dies mounted in a punch press or by contour roll forming. The choice usually depends on economic factors — mainly on the quantity of material to be processed. Because tooling costs are low, press-brake forming is suitable for small- and medium-lot production. Punch-press forming requires more expensive tooling but is advantageous for small parts and large quantities. The much higher tooling costs for roll forming restricts that method to large-quantity production.

RUBBER-PAD FORMING

There are many variations of the trapped rubber or rubber-pad forming process. Many of them are identified by the names of inventors or equipment manufacturers, e.g., Guerin, Wheelon, Marforming and Hydroforming. Although the methods differ in details, their characteristic advantage is that they minimize the number of tools required for forming sheet-metal parts. Furthermore, they reduce the amount of thinning suffered by the workpiece because the forming operation causes a gradual and continuous decrease in bend radii during a stroke. Ordinarily the forming operation is conducted with a rubber pad on the ram of a press and a form block on the platen as shown in Figure 71. The rubber pad, which returns to its original shape when the forming operation is complete, replaces dies with specific cavity configurations. This eliminates the need for the more expensive half of a die set. Some form blocks are shaped to act as the cavity instead of the punch. In some processes, the cavity is not completely filled with solid rubber. Instead, a thick rubber diaphragm containing hydraulic fluid in a pressure dome wraps around the blank during the forming operation. Form blocks are made inexpensively from low-cost materials such as epoxy resin, hardwood, cast iron, or steel depending on the severity of the operation and amount of service required. Forming pressures are usually in the lower range of 2500 to 15,000 psi.

With double-acting presses, rubber-pad processes can be used to produce deeply recessed parts such as domes, cups, and boxes. With single-acting presses, rubber forming is applicable to fabricating shallow recessed parts (e.g., beaded panels), bending straight flanges and sections or corrugated panels, and contouring flanging. In the latter two purposes, rubber-pad forming is an alternative to producing thin parts by extrusion or by secondary forming of extruded shapes. For instance, structural members with flanges such as channels and L- and Z-sections can be produced by rubber forming, as can curved channels and other sections. Flanging by rubber-pad processes is commonly practiced on a variety of materials including

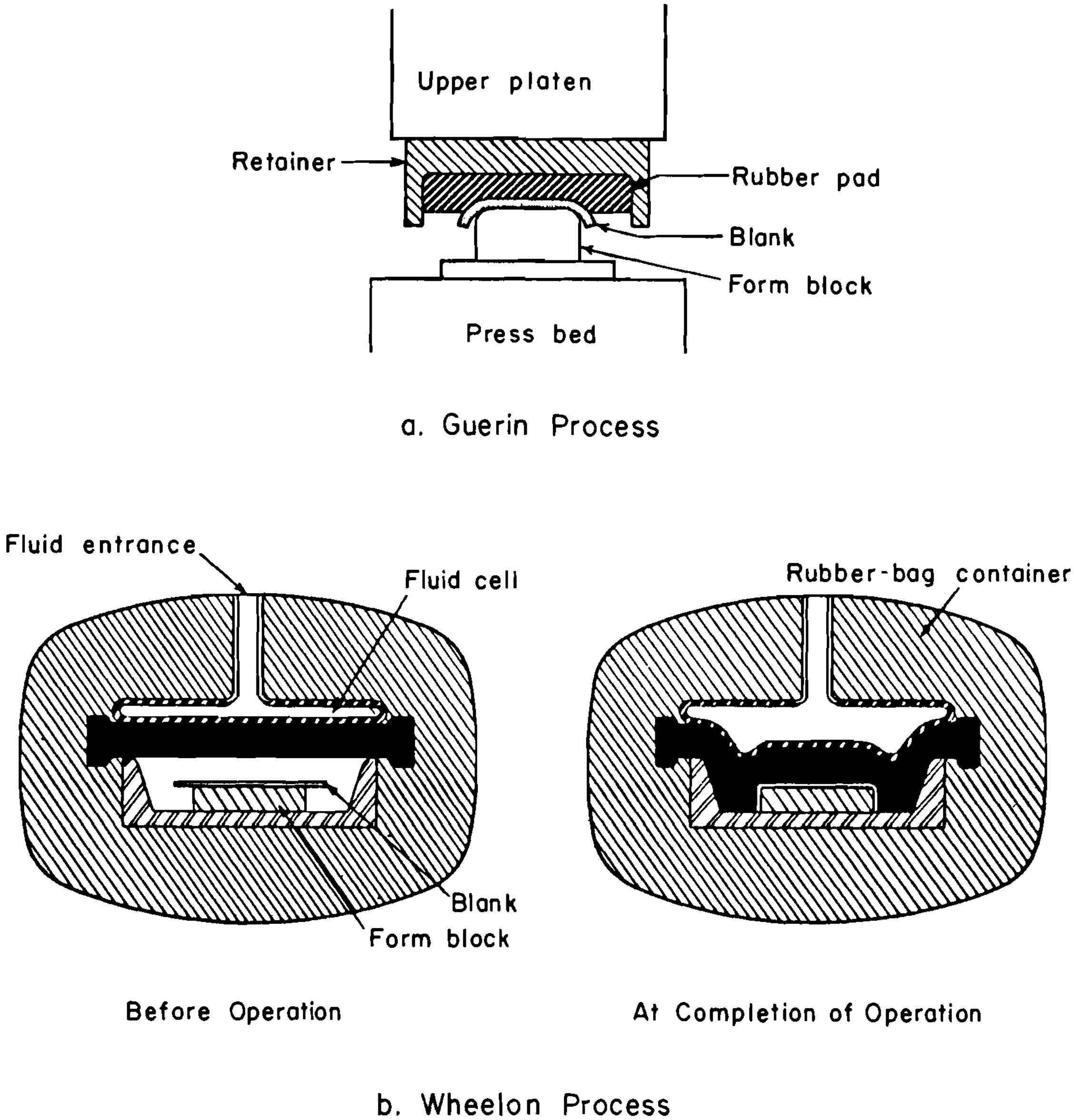


FIGURE 71. METHODS USED FOR TRAPPED-RUBBER FORMING[2]

aluminum alloys, some alloys such as 2024 in the T-4 condition, annealed and quarter-hard austenitic stainless steel, and titanium-base alloys.

Straight flanges can be bent easily if they are wide enough to develop adequate forming forces; if necessary, accessory tools can be used. Stronger materials require longer flanges to achieve tight bends. For forming pressures of 5000 psi or more, the ratio of flange length to sheet thickness should fall in the range from 10 to 18. Limiting bend radii are similar to those in brake forming and decrease the pressure supplied by the pad increases. In soft materials, flange angles can be held to a tolerance of 1 degree; strong materials such as half-hard stainless steel give more trouble; meeting a tolerance of ±5 degrees requires special care.

Stiffened panels and contoured flanged sections are often made by rubber-pad processes. Some components of the latter type provide alternatives to stretch formed straight extrusions or brake-formed sections. If the requirements for radii and flange height are not too severe, contoured flanged sections can be produced from titanium alloys at room temperature. Hot sizing is used to meet closer tolerances. Geometrical limits for stretch and shrink flanges that can be formed from some titanium alloys at room temperature are shown in Figures 72 and 73. Good parts can be produced under conditions falling

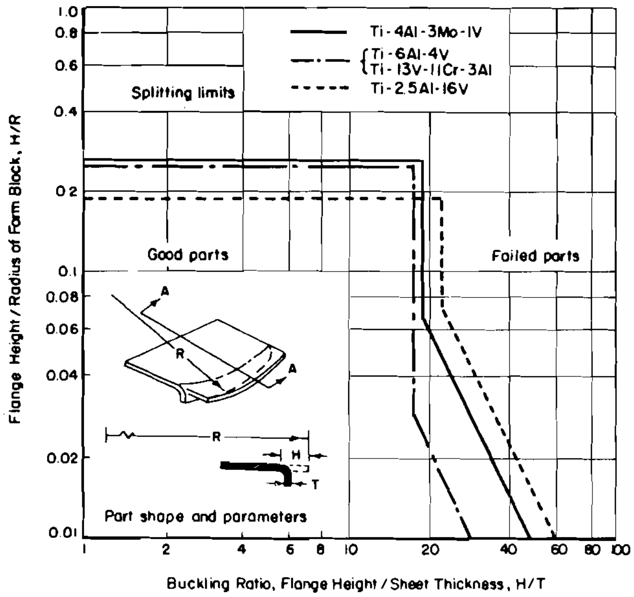


FIGURE 72. CALCULATED FORMABILITY LIMITS OF ANNEALED TITANIUM ALLOYS IN RUBBER-STRETCH-FLANGE FORMING AT ROOM TEMPERATURE[1]

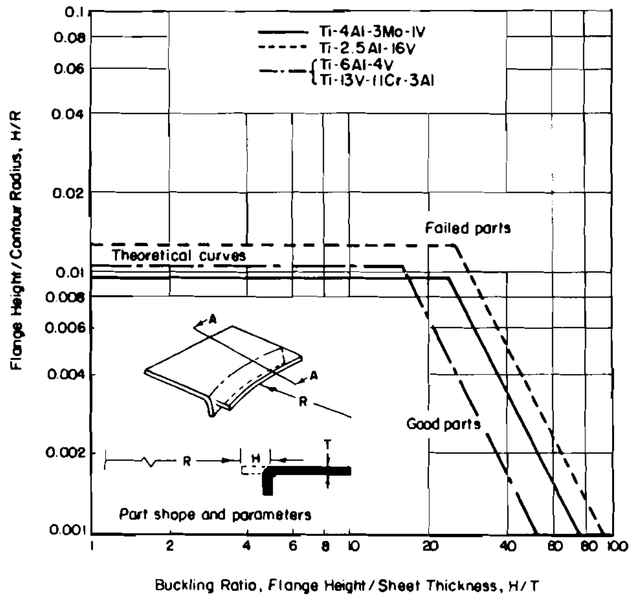


FIGURE 73. CALCULATED FORMABILITY LIMITS OF TITANIUM ALLOYS IN RUBBER-COMPRESSION-FLANGE FORMING AT ROOM TEMPERATURE[1]

below and to the left of the limit curves, for the materials identified on those charts.[1] In stretch flanging, splitting limits are controlled by the uniform elongation of the material and by the ratio of the flange height to the contour radius of the forming block. The tendency for buckling failure increases with the ratio of the flange height to thickness of the material. Buckling also depends on the ratio of the elastic modulus to the yield strength of the material. In shrink or compression flanging, higher forming pressures minimize buckling and wrinkling.

Because elevated temperatures improve ductility and lower flow stresses, a little work has been done with rubber-pad equipment at temperatures up to around 1100 F. Both the form block and workpiece are heated. The approach is usually limited to processing small parts; high-speed presses offer advantages in high-temperature forming.

Rubber-pad and -diaphragm forming is usually conducted on hydraulic presses. Most standard single-acting hydraulic presses can be equipped with a trapped rubber head for forming operations. The capabilities of the equipment depend on load capacity and strength of the container, which determine the maximum pressure generated in the rubber, and on the working area. Forming pressures typically vary from 2500 to 15,000 psi, but recent trends have been toward stronger synthetic rubbers and higher deformation pressures. Typical commercial presses designed for rubber forming have characteristics in the following ranges:

Work Area, in.^{2}	Press Stroke, inches	Strokes Per Hour	Press Capacity, tons
50	5	1200	125
300	10	1200	1800
800	12	90	4000
2200	15	20	7000

Several small parts are often made during the stroke but production rates for components made singly are approximately half the maximum stroking rate for the press. The working area of the press limits the dimensions of parts that can be formed by rubber-pad processes. The maximum length is less than for brake forming and far less than for extruded sections. Some of the largest presses, however, are capable of handling 8-ft shapes.

In most applications the rubber-pad process competes with matched-die processes for shallow or mild forming operations rather than with extrusion.

ROLL FORMING

Roll forming or roll bending is a continuous process for bending strip or sheet to a desired shape by passage through a series of contoured rolls. The process differs from form rolling because the cross-sectional area of the starting material remains essentially unchanged. Similar products (channels, hat sections, etc.) can be made by drawbench forming. That technique consists of pulling the strip through a series of stands containing undriven rolls. Most metals can be contour rolled from strip to shapes of uniform cross section, but the permissible speed and forming severity depends on the ductility of the material. The process is well-suited to producing large quantities and long lengths. Roll forming of structural shapes from aluminum, copper and steel, in thicknesses up to 3/8 inch is common. Less-formable materials such as titanium alloys and heat-resistant metals are less frequently shaped by this process.

Stringers, stiffeners, and body frames fabricated from standardized sections make up about 25 percent of the weight of sheet-metal parts in a typical airframe. The weight of an aircraft can be substantially lowered by modest reductions in weights of parts used in such large quantities. The savings can be achieved by forming sections of titanium alloys to smaller bend radii. The feasibility of doing so was demonstrated by Foster on an Air Force Contract.[3]

Foster, of the Boeing Company, roll formed titanium alloys at elevated temperatures in order to lower forming loads and to improve ductility.[3] Based on bend tests conducted at temperatures up to 1600 F, the optimum forming temperature was judged to be near 1450 F for specimens heated 10 minutes or less. Specimens formed below 1300 F had rougher surfaces and lower ductility; temperatures above 1500 F or exposure times longer than 10 minutes cause more contamination and lower ductility. Formability data obtained, on coupons cut from continuously rolled strip, with a hydraulically operated punch (speed, 10 ft/min) are given in Table 20. The study showed that formability is influenced by orientation of the bend with respect to the rolling direction of the coil stock. Transverse specimens, with the bend oriented in the direction most commonly employed for continuously rolled strip, gave the best results at room temperature. They could be bent to minimum radii smaller than those for longitudinal specimens by 1 to 1.5t (radius/thickness). The limiting bend radii for both specimen orientations are considerably smaller or better, at 1450 F than at room temperature. Directional variations in ductility also exist at 1450 F, but the bend direction for producing structural members from continuously rolled strip is in the least favorable direction. The Ti-6Al-4V stock exhibited significantly better formability than Ti-8Al-1Mo-1V material.

TABLE 20. MINIMUM BEND RADII FOR TITANIUM ALLOY COIL STOCK FOR CONTINUOUS ROLL FORMING[3]

Stock Thickness, inch	Bend Orientation(a)	Limiting Bend Radius at Temperature Indicated,(b) R/t: 80 F	1450 F
		Ti-6Al-4V	
0.050	L	5.5	--
0.050	T	4.0	--
0.060	L	5.0	1.0
0.060	T	4.0	1.7
		Ti-8Al-1Mo-1V	
0.050	L	6.0	--
0.050	T	4.5	--
0.060	L	6.0	2.0
0.060	T	4.5	2.5

(a) Specimen orientation with respect to rolling direction of the strip; e.g., fibered grains in longitudinal specimens were elongated parallel to the rolling direction and then ran around the bend in 90-degree angles.

(b) Smallest bend radius that did not produce cracks visible at 20X magnification in 10 consecutive acceptable bend specimens. Stock heated 10 minutes or less, 30-minute exposure caused deterioration of bend properties.

Decreasing the minimum bend radius by roll forming at elevated temperatures permits producing structural members with lighter weights. For 0.050-inch-thick stock, reducing the bend radius from 4.5t to 1.4t on typical hat and Z-sections would reduce the weight per foot by 9 percent.

Figure 74 shows the high-temperature rolling facility constructed for the continuous-roll-forming program.[3] Both the stock and the form rolls are heated by infrared radiant lamp panels. The 27-ft long stock preheating chamber has 6 lamp panels (24-kw lamps) in the entry zone. The central heating zone and the third or stabilization zone of the furnaces each have 6 lamp panels (6-kw lamps). The temperature of the material leaving the preheating chamber can be controlled to ±50 F. Cooling air is circulated between the inner and outer walls of the furnace to avoid exceeding temperatures permissible for the reflective surfaces and lamp end seals. The cooling air

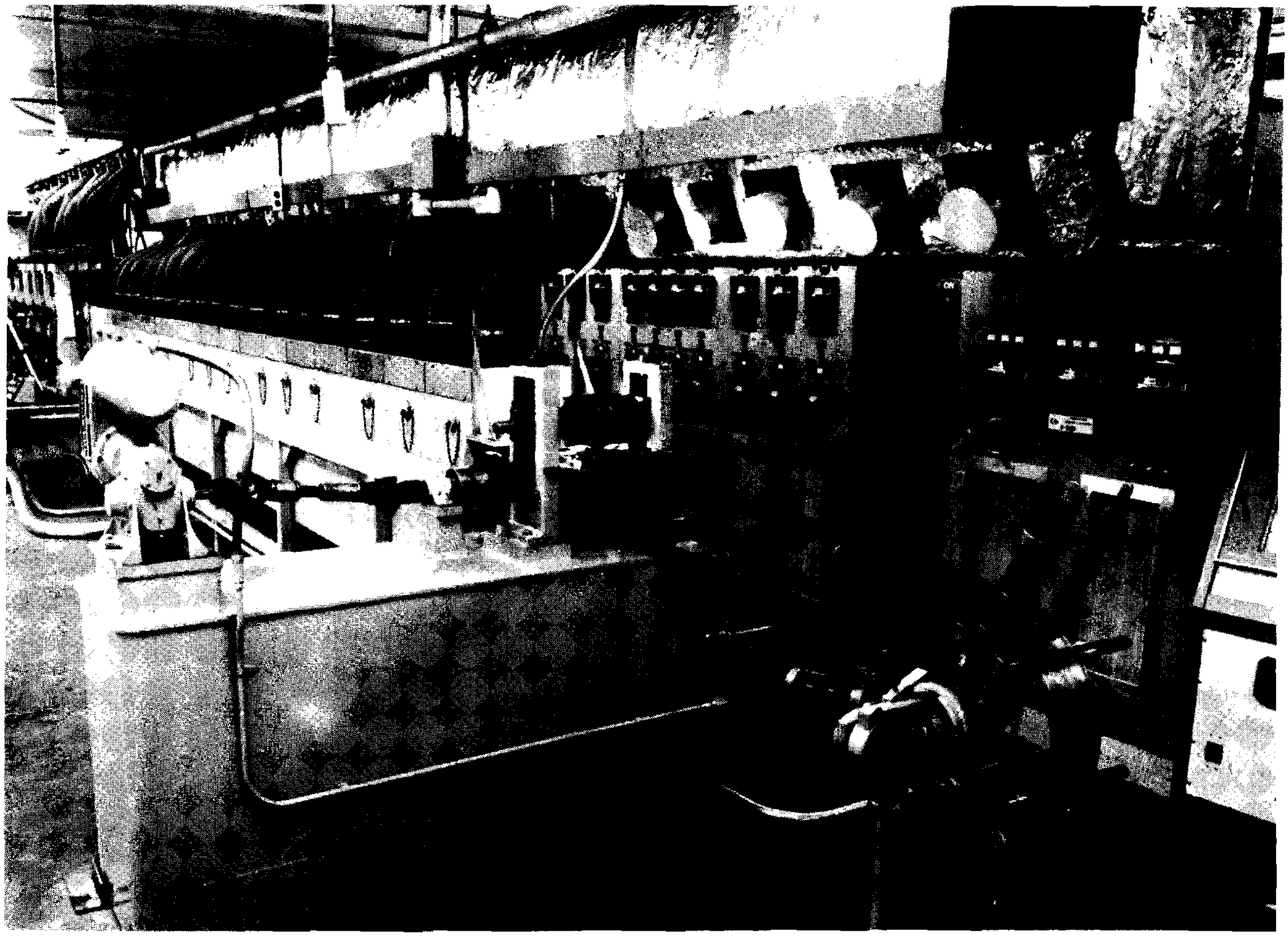


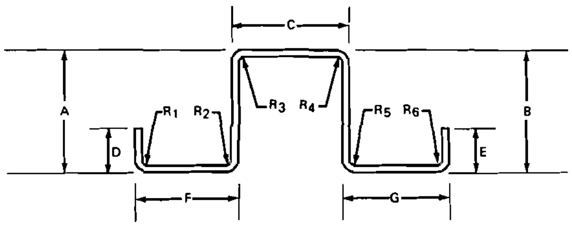
FIGURE 74. HOT ROLLING FORMING FACILITY (PHOTO COURTESY OF THE BOEING COMPANY)

is exhausted through flexible hoses and ducts. The form-rolling equipment consists of 10 roll stands and is driven by a 60-horsepower motor. The rolls were made from Incoloy 802 because it was the least expensive material exhibiting adequate strength at 1400 to 1500 F. The shafts of the rolls are water cooled. Incoming strip can be handled at speeds of 5 to 40 feet per minute. The roll-heating chamber is an assembly of two basic types of modules. The lamp modules for heating the rolls are identical to those used for preheating the strip. The roll lamp module enclosed the space between the inboard and outboard stands. The intermodular units, closing the space between the lamp units for the 10 stands, are similar in construction.

The intermodular units contain guides, to support the partly formed sections, made from 310 stainless steel flame sprayed with an oxidation- and abrasion-resistant coating. A straightening attachment, mounted behind the finishing stand, uses adjustable rolls to remove twist and bow from the formed product. A commercial material containing molybdenum disulfide was used as a lubricant for forming at 1450 ± 50 F.

In simulated production runs, approximately 540 feet of hat section and 520 feet of Z-section were produced. The hat section was formed from 0.050-inch-thick, 5.29-inch-wide Ti-6Al-4V strip in part lengths ranging from 40 to 56 feet. Figure 75 shows the shape, target and actual measurements of the hat section. Figure 76 gives information obtained on Z-sections produced from the same alloy (0.060 inch thick) in lengths exceeding 40 feet. It was reported that acceptable bend radii of 1.5t were formed consistently in the hat section, and fracture-free 1.2t radii were attained in the Z. Angular variations were ±2 degrees in the hat and ±1 degree in the Z. Both sections met tolerances of ±0.010 inch for the major mold line dimensions and ±0.020 inch for the return-flange heights.

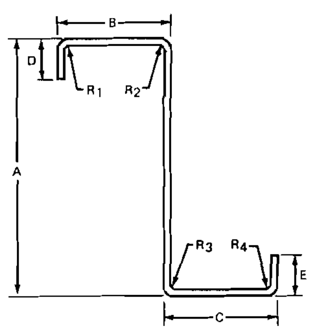
The roll-formed products were unusually straight. The cleaning process used to remove the lubricants and



	Target		Test Results	
Dimension	Nominal	Tolerance	Mean	Variation*
A & B	1.100	±0.010	1.105	±0.006
C	1.100	±0.010	1.101	±0.005
D & E	0.380	±0.020	0.400	±0.020
F & G	0.900	±0.010	0.901	±0.006
Bend angles at:				
R_1 & R_6	90°	±1°	92.0°	±2.6°
R_2 & R_5	90°	±1°	88.0°	±1.9°
R_3 & R_4	90°	±1°	88.0°	±0.5°
Bend radii at:				
R_1 & R_6	0.050	±0.010	0.075	±0.010
R_2 & R_5	0.050	±0.010	0.083	±0.007
R_3 & R_4	0.050	±0.010	0.080	±0.007

*Statistical variation from mean at 96% confidence level

FIGURE 75. DIMENSIONAL VARIATION IN HAT SECTIONS PRODUCED BY HOT ROLL FORMING IN SIMULATED PRODUCTION RUNS[3]



	Target		Test Results	
Dimension	Nominal	Tolerance	Mean	Variation*
A	2.500	±0.010	2.504	±0.006
B & C	1.100	±0.010	1.100	±0.006
D & E	0.400	±0.020	0.404	±0.006
Bend angles at:				
R_1 & R_4	90°	±1°	89.2°	±0.6°
R_2 & R_3	90°	±1°	88.5°	±0.5°
Bend radii at:				
R_1 & R_4	0.060	±0.010	0.070	±0.007
R_2 & R_3	0.060	±0.010	0.070	±0.007

*Statistical variation from mean at 96% confidence level

FIGURE 76. DIMENSIONAL VARIATION IN ZEE SECTIONS PRODUCED BY HOT ROLL FORMING IN SIMULATED PRODUCTION RUNS[3]

scale-contaminated layers decreased the section thickness by approximately 0.004 inch. The necessity of such treatments on hot-formed parts may limit applications of the process to stock thicker than 0.040 inch. Cleaning is a fairly expensive treatment.

Evaluation of the formed sections for mechanical and metallurgical properties, resistance to stress corrosion, and fatigue life revealed no detrimental effects of hot roll forming. The loss in strength of as-formed parts, caused by partial solutioning, is recoverable by a subsequent aging treatment. The mechanical properties of the hot-formed shapes were approximately equivalent to those of cold-formed material.

The hot, continuous roll-forming process for titanium is best suited to producing quantities of standardized sections large enough to amortize the substantial tooling and facility costs. The expense of new tooling for different shapes and trying the tools out would be expected to be high at the present stage of process development. Tooling costs for a particular shape are probably on the order of $90,000.

HYDROSTATIC EXTRUSION

The hydrostatic-extrusion process which utilizes a pressurized fluid between the billet and the tooling was first invented, at least in concept, as early as 1893. It was not, however, until the late 1950's and since that the process has been explored in terms of developing extrusion techniques and tooling designs for use of the process. Figure 77 shows the basic difference between conventional extrusion techniques utilized in manufacturing the

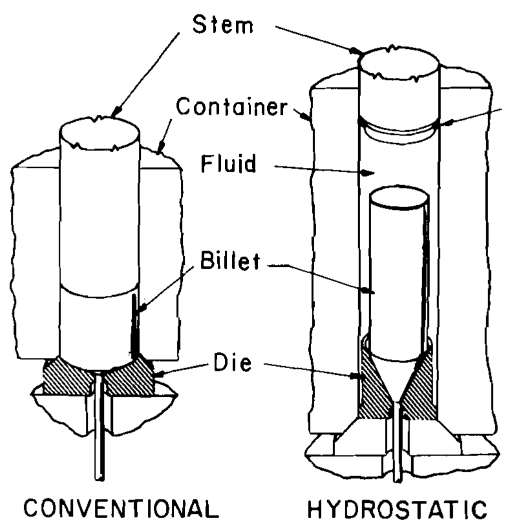


FIGURE 77. SCHEMATIC DIAGRAM OF CONVENTIONAL-EXTRUSION AND HYDROSTATIC-EXTRUSION PROCESSES

structural shapes discussed in this publication, and the basic hydrostatic-extrusion process. The most fundamental difference is the introduction, in hydrostatic extrusion, of a pressurized lubricant-fluid media between the billet and tooling which remains uniformly in effect throughout the extrusion stroke.

This fluid and its maintenance in a pressurized situation during the extrusion stroke results in the elimination of container friction and reduced die friction. The results of eliminating container friction and reducing die friction are (1) lower extrusion pressures for equivalent extrusion ratios obtainable by conventional extrusion methods, (2) larger reduction for equivalent extrusion pressures, (3) increased complexity of shapes that can be extruded, (4) longer extrusion billets resulting in greater throughput per push, and (5) better tooling life. In view of these potential advantages, the subsequent discussion shows examples of the types of products that have been extruded by this technique and the potential applicability of hydrostatic extrusion to the manufacture of structural shapes.

Work in this area began in the late 1950's both in England and in the Soviet Union. In the early 1960's, work was undertaken in this country at Nuclear Metals, Incorporated, Pressure Technology Corporation of America, and Battelle's Columbus Laboratories. The Nuclear Metals work used water as the pressurizing fluid in extruding copper, steel, beryllium, and yttrium under contract to the U.S. Atomic Energy Commission.(4) Pressure Technology Corporation studied fluid-to-fluid extrusion as a technique for fabricating brittle materials such as beryllium(5) and built several hydrostatic-extrusion presses which have been used in the United States for experimental purposes.

Initial Air Force-funded programs at Battelle were aimed at establishing basic process parameters for fabrication of materials of interest to the aerospace industry, namely: titanium, steel, and refractory metals.(6) These early studies developed extensive data on process conditions, fluids, lubricants, and tooling design which have provided much of the basic guidelines for subsequent work done in the United States up to the present time.

Subsequent studies at Battelle involved product-augmented extrusion of beryllium wire(7) and the design of a 15,000-ton press utilizing hydrostatic extrusion techniques.(8) Figure 78 shows some of the products extruded at Battelle on these Air Force programs and shows the Air Force-owned hydrostatic-extrusion tooling utilized in the manufacture of these various parts.

The results of these early efforts generated interest in other Government agencies, and work has been done for both the Army and Navy as well as the Air Force in recent years. Figure 79 shows Maraging 250 steel open- and closed-end tubes extruded for the U.S. Army Missile Command(9) which measured 2-3/4-inch diameter x 0.025-inch wall x 24 inches. Figure 80 shows large hydrostatic-extrusion tooling installed in Battelle's 2500-ton press and samples of both steel and aluminum extrusions made with integral ribs on a program for the Naval Ordnance Systems Command.(10) Figure 81 shows a small sample of thin-wall waveguide tubing extruded on the program for the U.S. Army, Harry Diamond Laboratories.(11) Recently completed studies involved extrusion of 2-3/4-inch diameter x 40-inch-long Inconel 718 mortar tubes on an Army contract for Watervliet Arsenal.(12)

Meanwhile Air Force-sponsored work at Battelle has continued, and is presently being directed towards utilizing *warm* hydrostatic-extrusion techniques for the manufacture of Ti-6Al-4V alloy tubing.(13) Figure 82 shows a sample of 1/2-inch diameter x 0.020-inch-wall Ti-6Al-4V tubing extruded at approximately 900 F at an extrusion ratio of 5:1. The study, still under way, is aimed at extruding titanium-alloy tubing of these dimensions, and lengths on the order of 10 feet for aircraft hydraulic-tubing applications.

The advantage of the *warm* hydrostatic extrusion technique is the ability to achieve higher extrusion ratios (by virtue of the lowering of flow stress at elevated temperatures) while still retaining the advantages of good surface finish and close dimensional control. For example, the Ti-6Al-4V tubing shown in Figure 82 had a surface finish of 10 to 15 microinches, CLA, and tube concentricity of ±2.5 percent, despite the fact that extrusion took place at a warm extrusion temperature.

Most of the work both in the United States and abroad has dealt with cylindrical parts, such as rounds, tubes, gear shapes, and hexagonal shapes. Techniques are now being explored at Battelle on an industry-sponsored program funded by 28 companies for the hydrostatic extrusion of both tubular and solid products as well as nonsymmetrical-shaped products. It can be anticipated that the technology developed to date on Government-sponsored programs, plus the technology now being transferred to industry through this industry-sponsored program and other work by individual companies, will soon result in a production base in the United States for supplying both aircraft and ordnance parts utilizing the hydrostatic-extrusion technique.

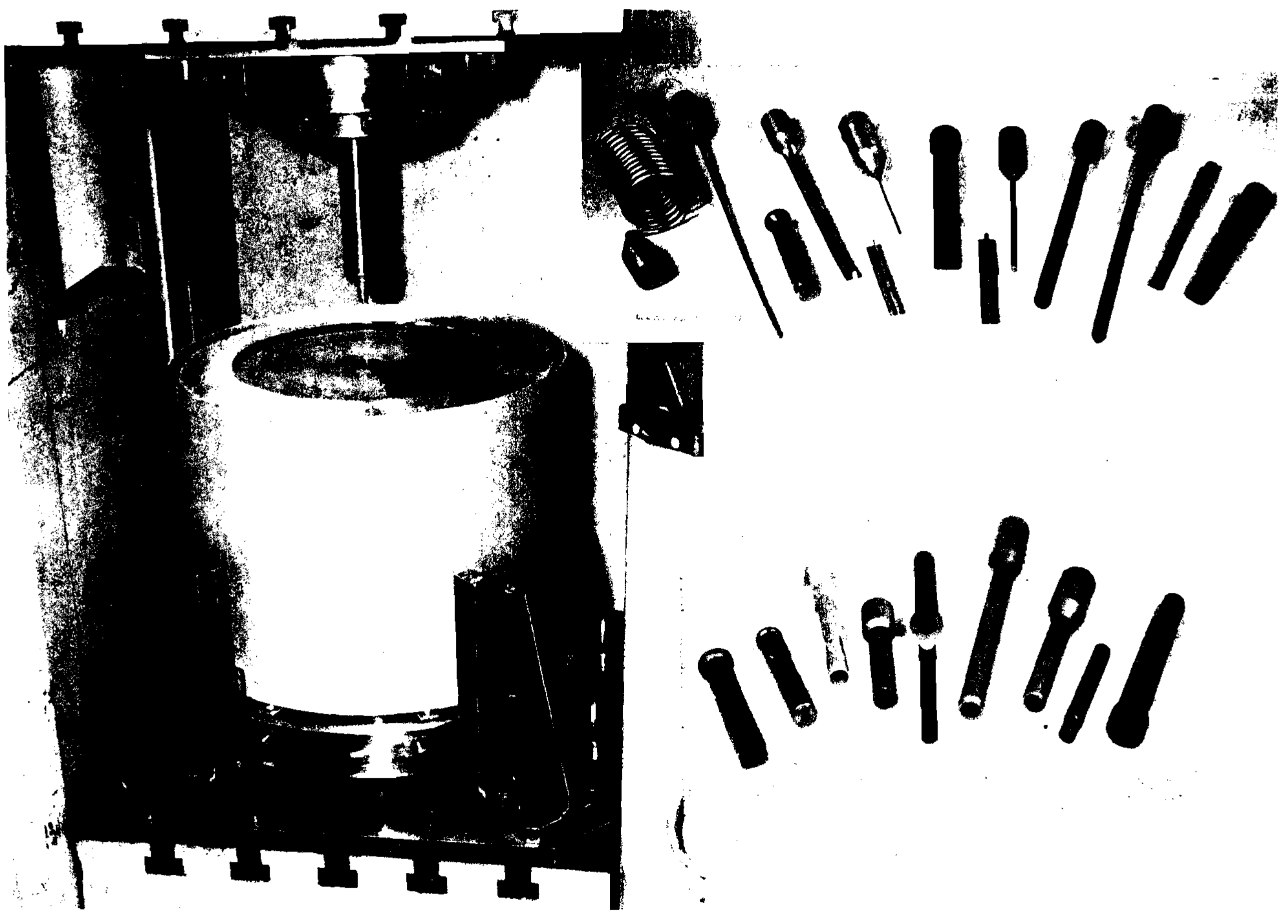


FIGURE 78. HYDROSTATIC-EXTRUSION TOOLING INSTALLED IN 700-TON VERTICAL HYDRAULIC PRESS

Container bore of 2-3/8-inch diameter x 20-inch length.

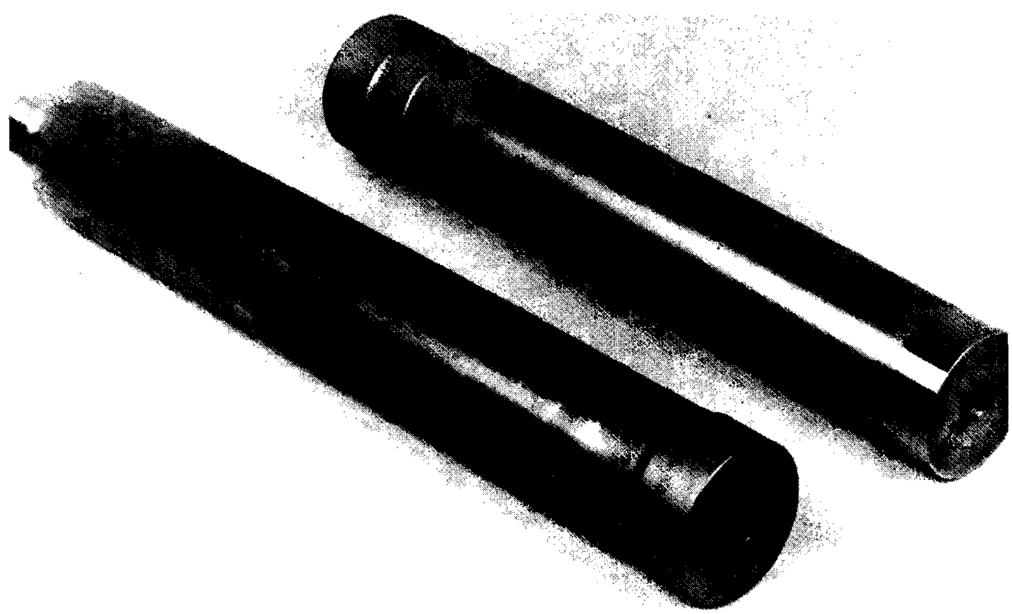


FIGURE 79. COLD HYDROSTATICALLY EXTRUDED MARAGING 250 STEEL CASES WITH END CAPS WELDED IN PLACE FOR BURST TESTING

Extruded on AMICOM study.[9]

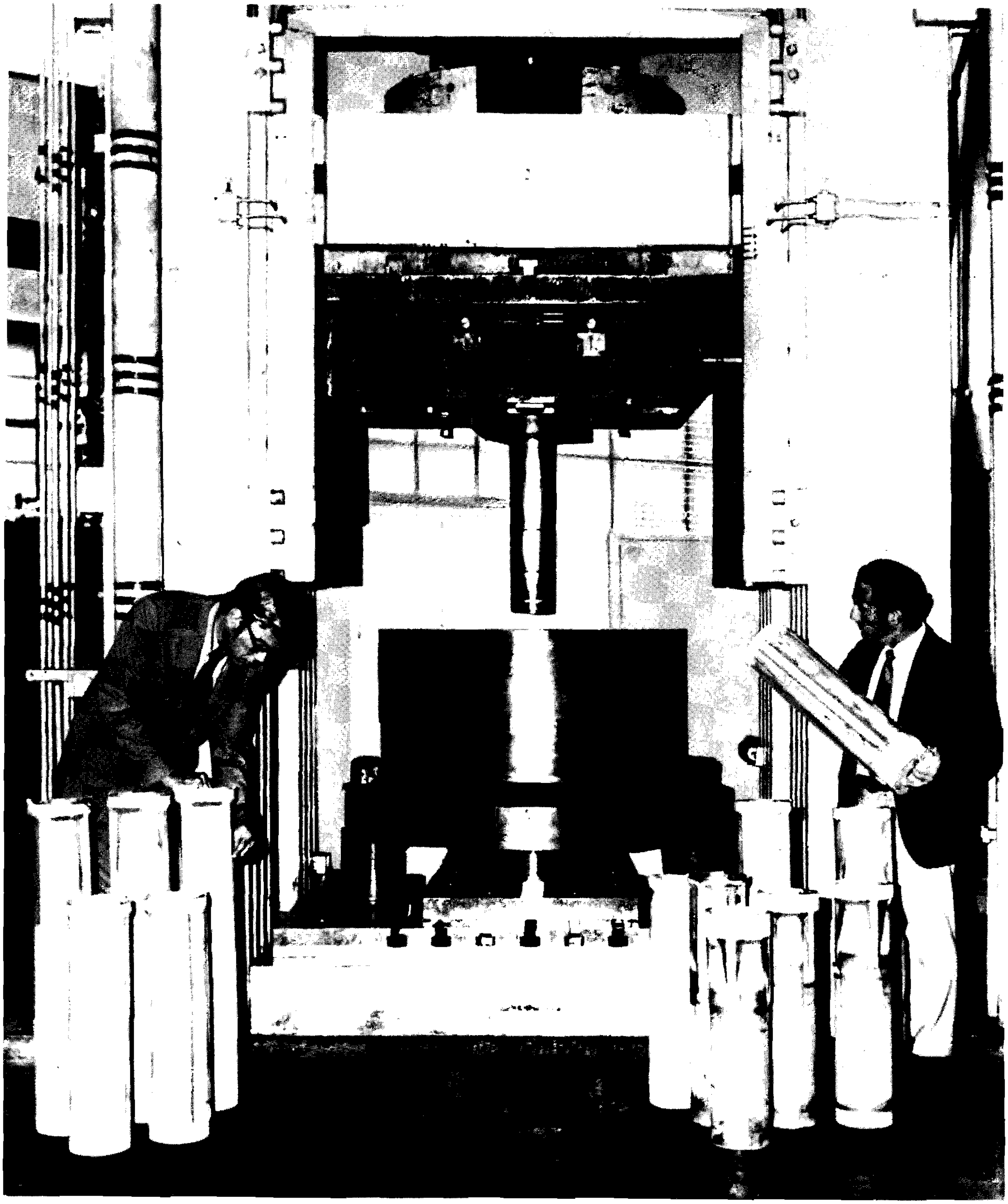
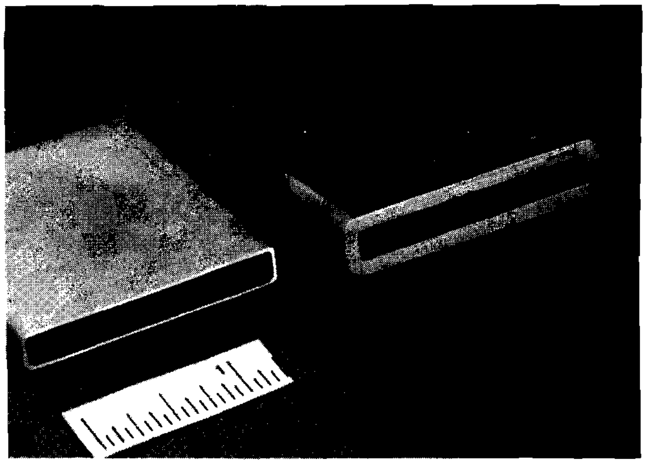


FIGURE 80. ASSORTED TUBULAR COMPONENTS OF ALUMINUM AND STEEL PRODUCED WITH BATTELLE'S HYDROSTATIC-EXTRUSION TOOLING INSTALLED IN 2500-TON HYDRAULIC PRESS[10]



Extruded Tube **Starting Tube Blank**

FIGURE 81. THIN-WALL 6061 ALUMINUM ALLOY HYDROSTATICALLY EXTRUDED FOR WAVEGUIDE APPLICATIONS[11]

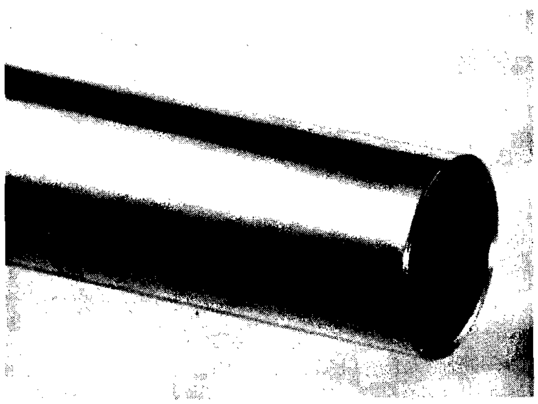
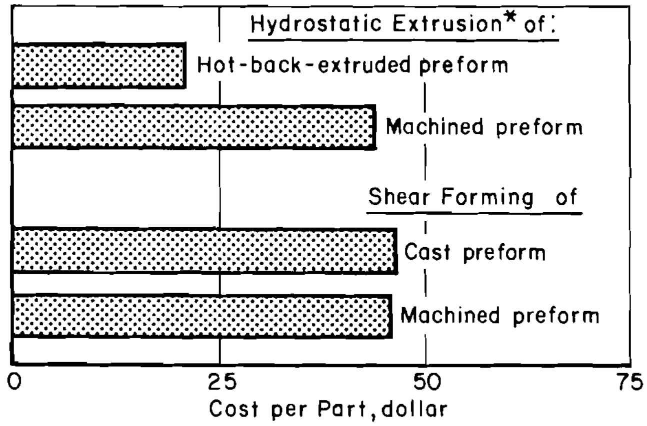


FIGURE 82. Ti-6Al-4V TUBE WARM EXTRUDED BY HYDROSTATIC TECHNIQUES AT 800 F[13]

0.5-inch OD x 0.020-inch wall.

It is believed that process advantages given above will result in reduced process costs. For example, Figure 83 shows some projected fabrication costs for a thin-wall missile case made by hydrostatic extrusion as compared to those for the present method of shear forming the same part.[9] The 50 percent cost savings per part demonstrated here is but one of several examples that can be potentially realized when hydrostatic extrusion is utilized in a production environment.

This process also, of course, shows promise for fabricating certain types of difficult-to-work materials to sizes not now available for utilization in military applications. For example, the Air Force efforts now under way for Ti-6Al-4V tubing show promise for ultimately providing this alloy in thin-wall tube form at a low enough price to make it attractive for use in aircraft manufacture.



* Based on 2:1 extrusion ratio only

FIGURE 83. FABRICATION COST COMPARISON FOR THIN-WALL MARAGING-STEEL MISSILE CASE

Quantity level = 50,000 units.[9]

In summary then, the hydrostatic-extrusion process should soon be available as a complement to, or replacement for, the conventional hot-extrusion process depending upon the application. The availability of this process in a production environment should result in production costs being reduced through reduced processing steps, and enable difficult-to-work materials to be fabricated at tolerable costs.

EXTRUSIONS FROM POWDERS

Ordinarily, structural shapes are rolled or extruded from wrought or cast billets. These standard approaches have several disadvantages when long products must be produced from nickel-base superalloys. Rolling is limited to relatively simple shapes and requires the production of large quantities (3500 feet) to be economically attractive. Although practical for smaller quantities, hot extrusion of superalloys has some limitations. Their high strengths and narrow hot-working temperature ranges restrict reduction ratios to approximately 4:1 to 8:1, thus limiting lengths and shape definitions obtainable. Subsequent machining to the precise dimensions preferred by designers is expensive.

To overcome those limitations, Gorecki and Friedman combined two advanced techniques and extruded superalloy powders to structural shapes by the "filled billet" process.[14] For the filled-billet approach, a composite round billet is assembled from components with suitable shapes as shown in Figure 84. The billet component destined to form the final product is geometrically similar to the final shape desired in the

product. That component, usually the core, has cross-sectional dimensions larger than those desired in the final product by the reduction ratio to be taken in the extrusion operation. For superalloy shapes, a powder-metal preform can be used as a component of the billet or the powder can be poured into a cavity of suitable size and shape. With either approach, the composite billet is sealed, evacuated, heated, and extruded through a round die. The die is ordinarily 1/2 inch larger than the circumscribing circle for the as-extruded shape. The filler material used to surround the superalloy can be an inexpensive metal of relatively low strength (such as mild steel) extrudable at the temperature suitable for superalloys. Since the filler material comprises 80 to 90 percent of the cross-sectional area of the composite, the filled billets can be extruded at reduction ratios higher than normal for the superalloy with relatively low loads. The product is later treated, usually by chemical dissolution or leaching, to remove the unwanted filler from the extruded superalloy shape.

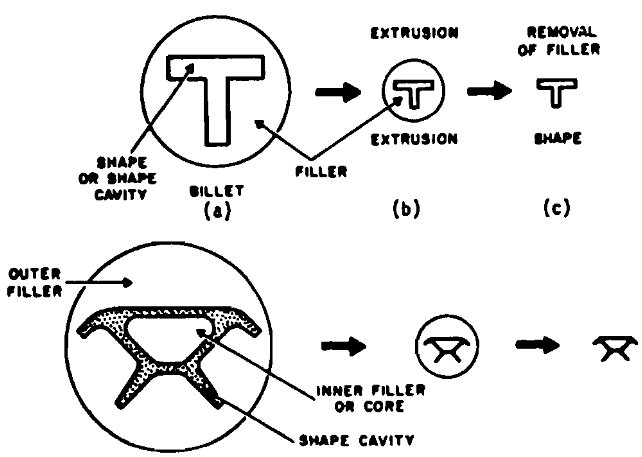
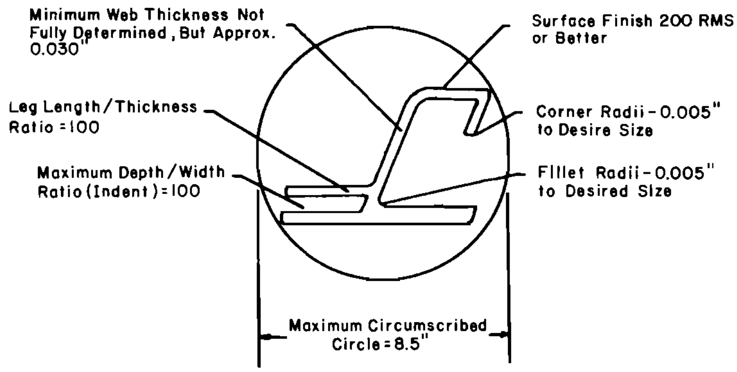


FIGURE 84. SUPERALLOY SHAPES PRODUCED BY THE "FILLED BILLET" TECHNIQUE[14]

Gorecki and Friedman developed procedures for extruding complicated shapes from superalloy powders by the filled-billet technique.[14] They showed that the mechanical properties of Inconel 718 and René 41 processed in that fashion met tensile and stress-rupture specifications. The process is capable of producing structural shapes, seamless hollows of round or irregular profiles, and shapes that taper from one end to the other. Some of the basic design limitations are shown in Figure 85. Sizes for structural shapes range from 1 inch up to limits set by the capacity of liners and presses available (probably 3-inch circumscribing circles in most cases).



TOLERANCES			
Height and Width of Legs	2" and up ± 10%	Angles	± 2°
Web Thickness	± 0.010 in.	Transverse Flatness Max. 0.020 in./in.	
Corner Radii	± 0.030 in.	Fillet Radii	± 0.030 in.

FIGURE 85. LIMITS AND TOLERANCES FOR SUPERALLOY SHAPES PRODUCED FROM POWDER BY THE "FILLED BILLET" TECHNIQUE[14]

The extrusion of powders by the filled-billet technique is in a medium-high state of development. Although not widely used in production it can be applied by most extrusion facilities with minor additions of equipment for machining billet components and for removing the filler material. The approach seems particularly suited to superalloys, and potential savings in processing costs are said to be appreciable. For many materials, however, the high cost of billet-preparation and product-removal operations are not outweighed by savings in raw material and final machining operations compared to those typical of conventional processes.

HIGH-FREQUENCY RESISTANCE WELDING

Structural shapes for applications such as stringer-panel sections of aircraft are ordinarily hot extruded or machined from simpler shapes. Those approaches have some limitations for materials like titanium alloys. The properties transverse to the major direction of deformation may be below average, and the producible thickness heavier than desired by the designer. For the latter reason, it is common practice to machine the entire surface of hot-extruded titanium shapes to remove contamination and to reach design dimensions. Because of the expense of machining, alternative methods of production have been considered. High-frequency resistance welding

of strip to form tees, channels, and other shapes is an approach with some promise.

High-frequency welding is widely used for the production of steel tubing, and welding equipment suitable for producing structural sections of titanium alloys is available commercially.[15] Figure 86 shows schematically the tooling arrangement used by DeSaw, et al., for producing a welded tee section. To form such a section, two strips, the potential stem and flange, are oriented at right angles and passed through the welding zone at a relatively high speed. Guides, not shown, cause the portions of the strips between the electrical contacts and the welding regime to form a V-shaped space or configuration. High-frequency electrical current (450-kH_z) enters the workpiece being welded from the sliding contacts and travels along the surfaces of the vee formed by the moving material. The high-frequency current is confined to the region immediately adjacent to the surfaces of the vee by skin and proximity effects. High-frequency electrical current tends to be concentrated in the skin in preference to the interior of a conductor. The proximity effect is the tendency for any two parallel conductors carrying oppositely directed currents to be attracted. If the conductors are mechanically restrained the currents still concentrate on adjacent sides of the conductors. Because of electrical resistance, the edges of the workpiece (which form the vee) are heated to temperatures required for welding. Thus, the process produces large current densities and high rates of resistance heating in narrow zones on both sides of the vee. At the apex of the vee, mechanical pressure is applied by squeeze rolls to forge the two strips together to complete the weld.

Despite the simplicity of the principles, details of the high-frequency resistance-welding process are important. Tooling must form the strip into the proper vee configuration and maintain the relationships during welding. The tooling must keep the incoming starting components electrically insulated from each other to prevent arcing

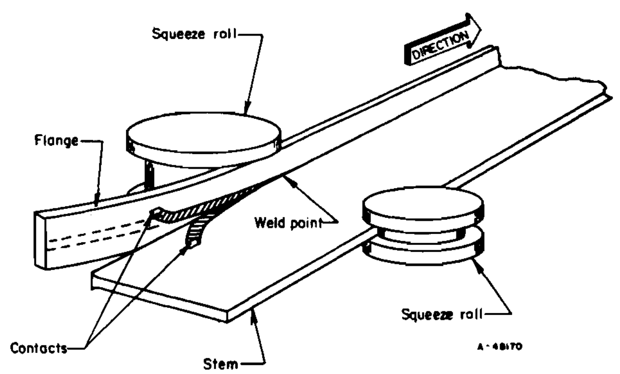


FIGURE 86. CONCEPT FOR HIGH-FREQUENCY RESISTANCE WELDING TEE SECTIONS[15]

and power losses, and feed the stock at uniform speeds. Since titanium reacts rapidly at elevated temperatures, with hydrogen, nitrogen, and oxygen, which can cause embrittlement, a protective atmosphere is needed. This can be provided by enclosing the strips and welded product in an argon-filled chamber extending from approximately 2 inches ahead of the weld point for several feet on the downstream side.

A certain amount of weld flash, consisting of metal squeezed out of the joint, characterizes joints welded by high-frequency resistance welding. Because the flash is irregular in shape and may contain unsound or contaminated metal, it must be removed. Flash removal is also desirable in order to produce smooth fillets at the junction between stem and flange elements. It has been demonstrated that the flash can be removed by machining (skiving) with a single- or multipoint tool either hot (in line) or cold (later). In-line removal is more appealing, but tool positioning is troublesome. That problem can be alleviated by preshaping the components so the edges to be joined are thicker than the sheet. Welded sections can be straightened by stretching.

The integrity of weldments destined for structural applications is ordinarily judged by nondestructive tests. The types of defects that can occur in high-frequency resistance welds are (1) incomplete fusion at the edge of the weld, (2) cracks in the upset portions of the base metal, and (3) local unwelded spots along the weld line. Ultrasonic immersion inspection employing a C-scan presentation and some types of eddy-current methods appear suitable for detecting such defects.[15]

DeSaw, Mishler and Randall demonstrated that 0.062-inch-thick strip of Ti-8Al 1Mo-1V or Ti-6Al-4V sheet can be welded to form tee sections at a rate of 150 feet per minute.[15] Tees of the latter material were produced at 300 feet per minute from 0.032-inch-thick sheet by the same technique. The process is considered to be in an advanced stage of development. Production of titanium structural shapes and tubing by high-frequency resistance welding would require engineering new methods of preparing strip edges efficiently, refinement of tooling for welding and skiving for the particular application, and refinement of fixtures for nondestructive testing of finished components.

DIFFUSION BONDING

Sometimes diffusion bonding is a feasible alternative to extrusion for producing structural shapes. Diffusion bonding is a generic term covering a variety of solid-state

joining processes including the specialized techniques sometimes identified as press bonding, deformation bonding, roll bonding, or extrusion bonding. The characteristic feature is that joining is accomplished without the presence of a bulk, liquid phase. The operation of joining an alloy to itself or to another alloy consists of bringing clean surfaces together and maintaining a suitable combination of temperature and pressure long enough to produce a suitably strong bond. The pressure should be high enough to exceed the yield strength of the surface asperities. Diffusion bonding is accomplished below the lowest melting point of the metals to be joined (normally at 0.6 to 0.9 of that temperature on the absolute scale).

The list of materials that have been successfully diffusion bonded (Table 21) indicates the versatility of the process.[16] Because low temperatures are satisfactory for some applications, it is sometimes feasible to diffusion bond components in the work-hardened, precipitation-hardened, or dispersion-strengthened conditions without degrading their mechanical properties. Joints in self-bonded weldments are ordinarily characterized by compositions and microstructures identical with the base metal. The practicality of diffusion bonding dissimilar metals permits production of some unusual composites, such as steel-titanium structural members, impossible to extrude. Porous tubing, another specialized product, can be produced by winding wire on a mandrel to form the tube and then diffusion-bonding the wire-wire contacts under appropriate conditions.[17]

TABLE 21. MATERIALS WHICH HAVE BEEN SUCCESSFULLY DIFFUSION BONDED[16]

	Self-Bonded
Carbon steels	Molybdenum
Low-alloy steel	Tantalum
High-alloy steel	Titanium alloys
Ni-base superalloys	Beryllium
Aluminum alloys	
	Dissimilar Materials
Titanium/stainless steel	Aluminum/stainless steel
Titanium/boron	Aluminum/nickel
Titanium/beryllium	Aluminum/titanium
René 41/4130 Steel	Copper/stainless steel

The several methods of producing diffusion-bonded titanium structural components differ in the type of equipment employed and the amount of deformation occurring during processing. In theory, bonding should occur immediately if two smooth, clean surfaces are brought into contact. In practice, however, some pressure is necessary to increase the true contact area and sliding is desirable in order to disrupt oxide films which interfere with diffusion.

The production of titanium sandwich structures is an example of a diffusion-bonding process characterized by negligible deformation. Cover sheets have been welded to honeycomb cores by the atmospheric load acting on the exterior surfaces of an evacuated assembly. The retort and cover sheets, of course, have a larger area than the area of contact between the core and facing sheets so the pressure is higher than atmospheric. The more complicated processes such as roll bonding, extrusion bonding, and press bonding are characterized by larger deformations.

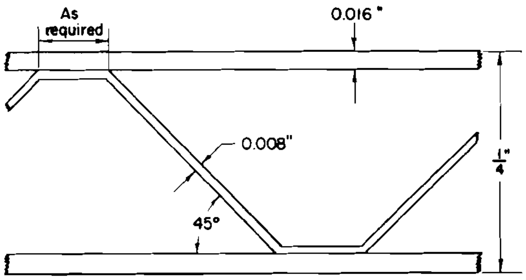
Roll bonding is a technique for producing solid-state bonds between components of an assembly during the short time needed for hot rolling.[18] It is an earlier variety of the filled-billet technique described above for producing structural members from superalloy powders. This sacrificial-metal, diffusion-bonding process is practical for a large number of materials. The principal requirements are that the constructional alloy and the sacrificial metal have somewhat similar hot-working characteristics and that the sacrificial metal can be removed economically without damaging the structural shape.

Roll bonding is technically feasible for producing a variety of long structural members in wide widths. For example, Figure 87 shows a truss-core sandwich panel, fabricated by diffusion bonding, before and after rolling. This pack was designed for a rolling reduction of 60 percent. The pack to produce the titanium alloy panel consisted of the following components:

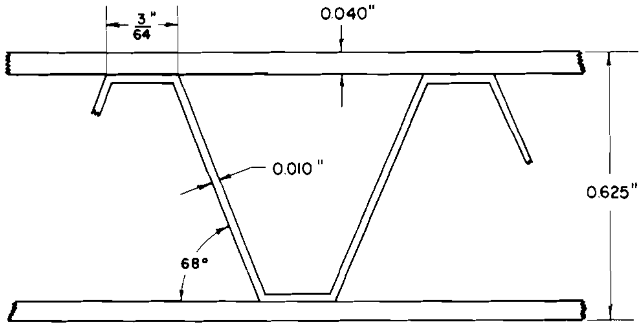
- Cover sheets of titanium alloy
- A core made from individual strips, or a corrugated sheet of titanium
- Wedges of mild steel as fillers to support the core.

These components were surrounded by a steel envelope which was evacuated and sealed prior to rolling the assembly on a standard plate mill. The pack of steel and titanium was then given a reduction of 60 percent at temperatures between 1400 and 1795 F (760 and 980 C). Such a treatment, combined with some soaking at those temperatures, insures good diffusion bonding of the titanium joints.

After forming to the shape desired, the filler metal is removed by chemical dissolution. Boiling nitric acid is a suitable solution for removing a mild-steel filler from a titanium sandwich. Hot rolling in the direction of the corrugations decreased the thickness of the cover plates by 60 percent and, because spreading was minimal, changed the angle of the truss from 68 degrees to 45 degrees. The thickness of the nonhorizontal truss mem-



a. Desired configuration



b. Starting configuration

FIGURE 87. CROSS SECTIONS OF A TRUSS CORE SANDWICH PANEL BEFORE AND AFTER ROLLING[18]

bers was reduced in proportion to the angle of the truss. Large titanium sandwich panels up to 35 feet long have been produced by roll bonding in experiments with commercial steel-mill equipment.

Roll bonding can be performed by conventional rolling practices on commercially available equipment. The components making up the pack have to be machined and it is likely to be most efficient to have this work done at a separate facility and the pack delivered to the mill. The pack assembly, purging, and evacuating steps are straightforward but require welding equipment and vacuum pumps. The use of the pack eliminates the need for special furnaces with atmospheric control. Limitations on length and width of roll-bonded products are set by dimensions of heating furnaces available at steel mills. As for the preparatory work, tedious and labor-intensive leaching treatments are best conducted in a facility separate from the roll mill. Roll bonding is of particular interest for producing structures with complex cross sections. Most of these comments also apply to the extrusion-bonding and filled-billet extrusion processes.

Roll welding and leaching of the steel filler metal causes no deterioration in the mechanical properties of the Ti-6Al-4V alloy sheet. Table 22 shows that annealing after processing developed strengths and ductilities essentially the same as those in the starting material.

TABLE 22. TENSILE PROPERTIES OF Ti-6Al-4V SHEET IN THE ANNEALED CONDITION[18]

Specimen Orientation	Tensile Strength KSI	Tensile Strength MN/m^2	Yield Strength KSI	Yield Strength MN/m^2	Elongation, percent
			As-Received Material		
Longitudinal	145	1000	137	945	16
Transverse	145	1000	137	945	12
			Truss Material		
Longitudinal	151	1041	136	938	12
Transverse	146	1000	137	945	11

Extrusion-bonded products can be produced from composite billets prepared in the manner described earlier for roll bonding. For simple applications, inert powders can be used as the filler for the structural-metal components, but the composite billet ordinarily includes a leachable, sacrificial metal. The maximum product size depends on the equipment available. The shapes are limited mainly by the ingenuity of the designer. Figure 88 shows some hollow sections made from filled billets.

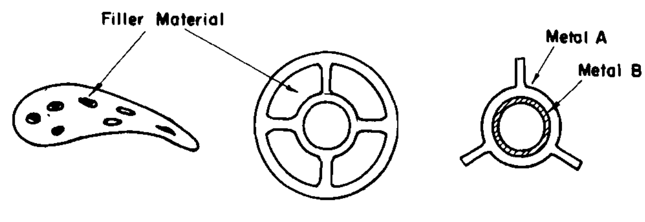


FIGURE 88. EXAMPLES OF HOLLOW SECTIONS PRODUCED BY EXTRUSION AND LEACHING

The pressure needed for diffusion bonding can also be applied by a press. For press bonding, clean details of parts of suitable size and shape are assembled with appropriate tooling, usually made from ceramic material, and sealed in a retort. The retort is preheated, then placed between ceramic heating platens attached to the stationary and moving platens of a hydraulic press. Both heat and pressure are transmitted by the ceramic platens, which are heated by embedded resistance elements, to the retort containing the details to be bonded. By using exterior tooling to provide restraint, stresses perpendicular to the ram motion can be developed and isostatic pressure established. The tooling inside the retort is designed to control the amount of deformation at various locations in the assembly. Some flow is desirable in order to disperse films of oxides or other contaminants on the interfaces and, thus, aid diffusion bonding. Appropriate load-temperature conditions cause creep which can be used to

produce recesses, tapers, and fillets with tight radii. The tooling can be reused.

Press bonding is a versatile process reasonably well suited to limited production. When necessary, bonds can be produced in any desired plane. Complex parts can be produced with close-to-finish dimensions. Heavy sections of press-bonded titanium produced from thin laminates usually exhibit a finer grain structure and superior properties than those of massive forgings.

A large variety of components have been produced from titanium by press diffusion bonding. Most of them were parts that ordinarily would have been forged on a heavy press (18,000 to 50,000-ton capacity) and then machined to shape. One such example is a helicopter rotor hub weighing 230 pounds and 54 inches in maximum diameter. The press-bonded substitute for the conventional 1000-pound forging weighed 385 pounds and thus saved raw material and machining costs.[16] Other products include some that might have been made by processes involving extrusion. The diffusion-bonded components made from Ti-6Al-4V for the chamber of the synchrotron at Argonne National Laboratory resembled the stiffened skins of aircraft fuselages and wing boxes. It contained 15,000 ribs approximately 0.040 inch thick, joined to caps 0.050 inch thick, and 0.025-inch skins. Diffusion-bonded beams 18 inches x 41 feet have also been produced.

Many of the titanium fittings ordinarily made by machining from closed-die forgings may be made by diffusion bonding. Figure 89 shows some of the parts for the B-1 considered by Reidelberger and Reinsch to be the most likely candidates for fabrication by bonding.[19] The mention of stringers, wing fairing frames, and nacelle support beams is noteworthy because bonding represents an alternative from fabrication of extrusions. Titanium alloys, particularly Ti-6Al-4V, have properties particularly suitable for diffusion bonding. Thin surface oxides, which would retard bonding, dissolve in inert atmospheres above 1250 F. Diffusion occurs in titanium at satisfactorily rapid rates at temperatures below the beta transus. This characteristic permits retaining the microstructures of the thin details (parts) used to build up the bonded components and sometimes enhances fracture toughness and fatigue resistance.

Press diffusion is a flexible process suitable for producing parts with deep pockets, thin-gage sections, close tolerances, and large-plan areas. An economic comparison mentioned by Reidelberger indicates that the breakdown point for diffusion bonding and the forge-machine approach to fabrication is near 400 square inches.[19] Diffusion bonding offers cost advantages for larger areas. Capital costs of the equipment are held down because much of the tooling is reusable.

No specific information suitable for a direct comparison of mechanical properties of structural shapes (e.g., channels) that can be made by either extrusion of roll bonding is available. Consequently, the data presented by Brunken for roll-diffusion-bonded skin structures made from Ti-6Al-4V are of interest.[20] In 1970, he produced four panels 1.4 inches thick, 35 inches wide, 108 inches long by diffusion bonding. After removing the internal mandrels by mechanical and leaching methods, surface contamination was removed by chemical milling. Ultrasonic inspection by the pulse-echo method detected no bond defects in 256 feet of joint. Thickness measurements for the individual panel components are given in Table 23. They show that the roll-diffusion-bonding process can produce integrally stiffened skin structure to standard aircraft dimensional tolerances. Dimensions for panels from different packs should not be compared because the packs were rolled by different practices to different final thicknesses. Industrial rolling equipment makes it possible to consider producing structures up to 70 feet in length and 190 inches in width.

Tensile tests were made on the panel skin material and the panel cap material. They showed that diffusion bonding at 1700 F changed the properties from those of the as-received material. The approximate changes amounted to decreases of 8 ksi in ultimate strength and 11 ksi in yield strength, and an increase in elongation values of 2 to 4 percent. Nevertheless, the properties measured exceeded the minimum specified values for annealed Ti-6Al-4V.

Fatigue tests on excess material from the skin of bonded panels gave the results shown in Figure 90. When compared on the basis of percentage of ultimate strength, the smooth fatigue properties of the as-bonded material agreed with those for as-received materials.

Over $7 million was spent on developing diffusion-bonded technology before 1967.[21] The major organization in the field believes the process is cost competitive with older practices for producing deep-pocketed structural shapes, hollow parts and integrally stiffened skins.[16] The manufacturing facility at North American Rockwell occupies 50,000 square feet and is equipped with presses ranging from 100 to 18,000 ton in load capacity. The installation is capable of press bonding components fitting within retorts ranging up to approximately 6 feet in width and 25 feet in length.

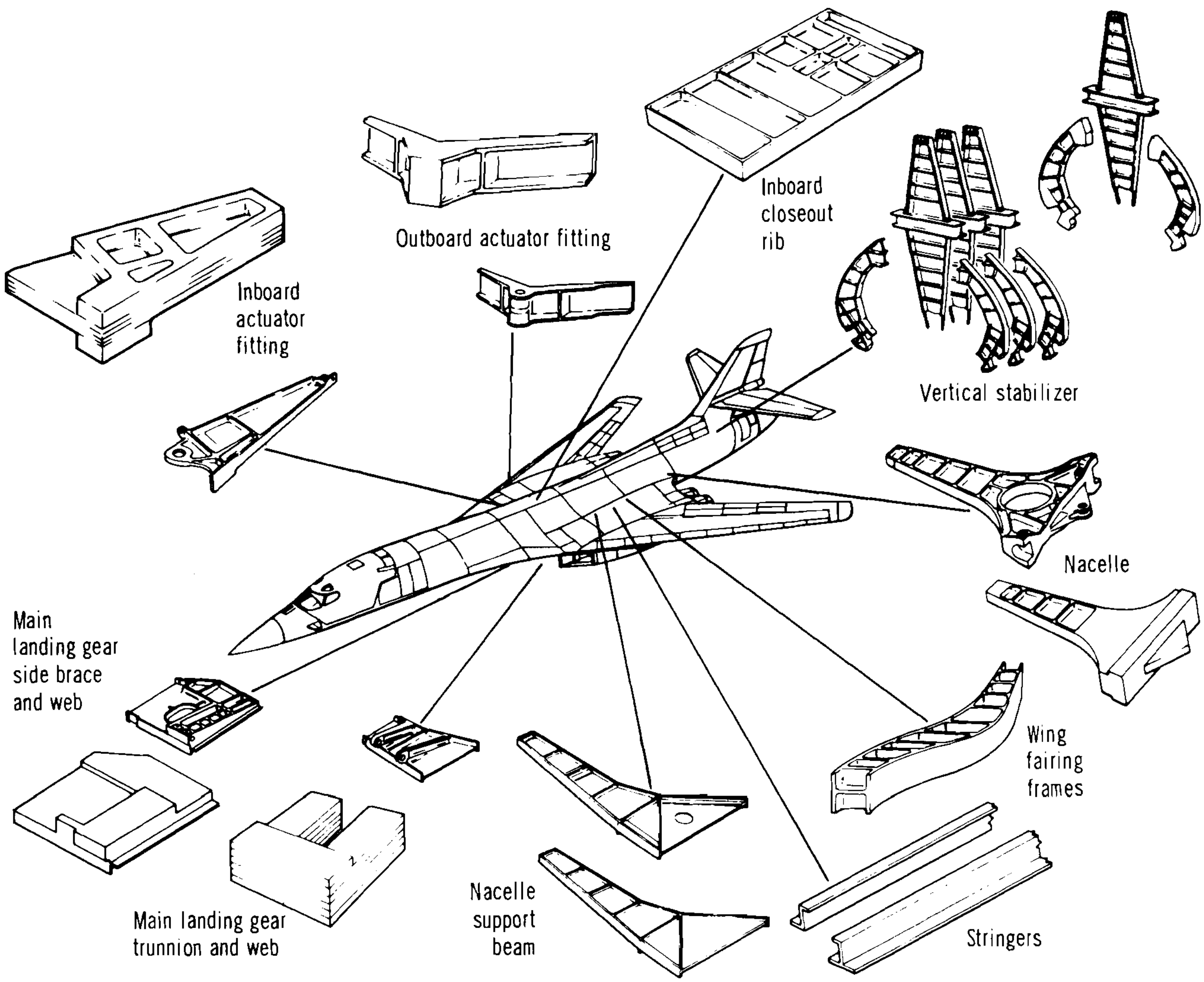


FIGURE 89. THESE PARTS FOR THE B-1 AIRCRAFT ARE ALL CANDIDATES FOR DIFFUSION BONDING[19]

In many instances, new capital investment would be required if other fabrication methods were used.

TABLE 23. DIMENSIONAL EVALUATION OF ROLL DIFFUSION BONDED STIFFENED SKIN PANELS[20]

Measurement Type	Measurement Number	Program Target Dimensions, inch	Accepted Structural Design Dimensions, inch	Measurements(a), inch Pack 1	Measurements(a), inch Pack 2
Panel Height	60	1.425 ± 0.010	1.425 ± 0.030	$1.425 {+0.005 \atop -0.010}$	$1.425 {+0.015 \atop -0.050}$
Skin Thickness	36	0.125 ± 0.010	1.125 ± 0.010	$0.125 {+0.000 \atop -0.010}$	$0.125 {+0.006 \atop -0.005}$
Cap Thickness	14	0.080 ± 0.010	0.080 ± 0.010	$0.080 {+0.004 \atop -0.006}$	$0.080 {+0.003 \atop -0.005}$
Web Thickness	10	0.080 ± 0.010	0.080 ± 0.010	$4.053 {+0.009 \atop -0.014}$	$4.037 {+0.010 \atop -0.007}$
Web Spacing	27	--	--	$4.053 {+0.009 \atop -0.014}$	$4.037 {+0.010 \atop -0.007}$

(a) Measurements reflect deviations, at different locations, from program design dimensions. Measurement for Pack 1 were made on Panels 3 and 4, those for Pack 2 represent Panels 1 and 2. Data are indicative of tolerances that can be produced from a single pack roll bonding assembly.

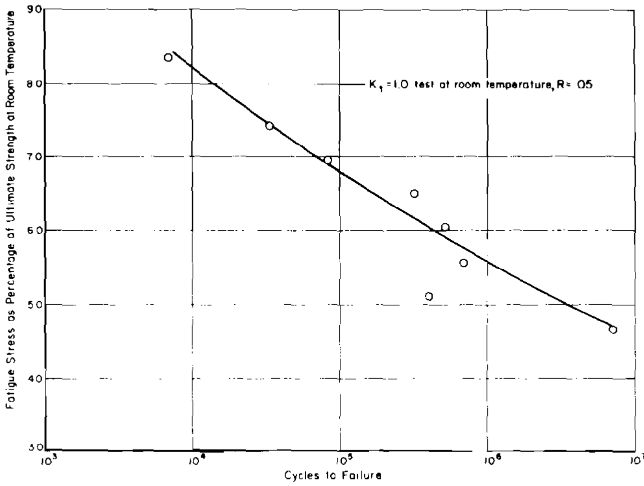


FIGURE 90. FATIGUE DATA FOR Ti-6Al-4V BASE MATERIAL AFTER ROLL BONDING[20]

ROLLING WITH HEATED ROLLS

Other novel approaches to producing structural shapes to close tolerances are receiving experimental attention. In two such programs, the practicality, potential advantages, and cost effectiveness of using heated rolls in hot-rolling mills are being investigated. In conventional hot rolling, the rolls are much colder than the stock, and chilling of the workpiece surfaces is pronounced.

Popoff, Byrer, and Fiorentino, of Battelle's Columbus Laboratories modified a rolling mill to achieve surface temperature at the roll surfaces up to 1500 F.[22] Strips of Ti-6Al-4V 0.053 and 0.127 inch thick were preheated to 1550 F and 1825 F, respectively, and then reduced by passing through heated rolls. The 8-inch rolls consisted of tool-steel shafts and superalloy sleeves. The sleeves were heated by induction with a 100-kw unit to temperatures as high as 1500 F. Under those conditions the rolling loads for a 25 percent reduction in thickness on stock heated to 1550 F were approximately 38,000 pounds per inch of strip width. That value is much less than values of 75,000 pounds and 50,000 pounds measured in experiments with conventional hot rolling (unheated rolls) for stock with initial thicknesses of 0.053 inch and 0.127 inch, respectively. The use of heated rolls was also shown to permit heavier rolling reductions and to reduce the tendency of brittle materials (such as tungsten and beryllium) to crack during deformation.

Development work on the process of deforming metals with rolls heated to high temperatures is continuing. In the larger scale investigation the rolls will be heated by radiation from infrared lamps; bearings and journals will be water cooled. The program includes experiments on rolling structural "L" shapes, from square bar stock, on a modified 2-high production mill. The L shapes are to be produced from Ti-6Al-4V and Hastelloy X.

Rose and Carpenter of Solar Division of International Harvester, conducted development work on isothermal rolling of shapes from titanium and superalloys.[23] Heated tooling, made from refractory metals, is used to avoid chilling of the workpiece. The equipment provides for passing an electric current between the rolls to heat both rolls and workpiece. As the workpiece is heated for only the few seconds it is in contact with the rolls, contamination is negligible even after several passes at 1800 F. The refractory-metal rolls operate satisfactorily in air. By maintaining isothermal conditions, low deformation rates can be employed and this feature lowers the flow strength of the workpiece considerably.

Some of the isothermal shape rolling was concerned with producing 0.063-inch-thick Z-sections from Ti-6Al-4V sheet stock. The objective was to attain the desired configuration by producing a significant amount of metal flow and redistribution of material. In that respect it differed from the roll forming (bending) approach investigated by Boeing.[3] Hence, the roll-separating capacity of the rolling equipment, 25,000 pounds, was approximately five times as large as that used for roll forming. Some preliminary work has also been conducted on isothermal rolling of T- and I-shapes from Ti-6Al-4V round bars. The goal is to produce the I-shape in three rolling passes. In the first pass the bar stock would be rolled to a dumbbell shape; the roll gap would be fixed but the ends of the dumbbell would not be confined. The web of the I would be rolled to the desired thickness in the second pass. The bulbous ends of the dumbbell would be used in the final pass to prevent changing web dimensions.

The heated-roll and isothermal shape-rolling processes are in very early stages of development. Hence, it is too soon to judge whether they will become viable competitors to extrusion processes for producing structural shapes.

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APPENDIX A

LIST OF AIR FORCE-SPONSORED PROGRAMS AND ACQUISITION SOURCES

FORM ROLLING

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
F33(615)-67-C-1796	FORM ROLLING STRUCTURAL SHAPED TUBING	AFML-TR-70-319	AD 882 043
F33(615)-3545	MANUFACTURING METHODS FOR FORM ROLLING CLOSE TOLERANCE SHAPES OF SUPERALLOYS	AFML-TR-69-186	AD 860 456
AF33(615)-3049	A PRODUCTION PROCESS FOR LARGE SOLID MOTOR CASES, INTERNAL ROLL-EXTRUDED	AFML-TR-68-116	AD 835 224

PROPERTIES

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
ALUMINUM			
F33(615)-68-C-1709	FRACTURE TOUGHNESS, FATIGUE, AND CORROSION CHARACTERISTICS OF X-7080-T7E41 AND 7178-T651 PLATE AND 7075-T6510, 7075-T73510 X7080-T7E42, AND 7178-T6510 EXTRUDED SHAPES	AFML-TR-69-225	AD 861 922
F33(615)-71-C-1054	MECHANICAL PROPERTIES OF 7049-T73 AND 7049-T76 ALUMINUM ALLOY EXTRUSIONS AT SEVERAL TEMPERATURES	AFML-TR-72-2	AD 740 878
F33(615)-71-C-1261	ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS	AFML-TR-72-196 Volume II	
TITANIUM			
F33(615)-70-C-1680	THE MANUFACTURE OF AIRCRAFT QUALITY HYDRAULIC TUBING WITH THE Ti-3Al-8V-6Cr-4Mo-4Zr ALLOY	AFML-TR-71-111	AD 727 779
AF33(615)-3089	DETERMINATION OF PROCESSING REQUIREMENTS FOR HIGH STRENGTH TITANIUM ALLOY TUBING MANUFACTURE	AFML-TR-68-263	AD 846 591
AF33(615)-5080	DEVELOPMENT OF ENGINEERING DATA ON TITANIUM EXTRUSIONS FOR USE IN AEROSPACE DESIGN	AFML-TR-67-189	AD 818 780
AF33(615)-1674	PRODUCTION TECHNIQUES FOR EXTRUDING, DRAWING AND HEAT TREATMENT OF TITANIUM ALLOYS	AFML-TR-68-349	AD 848 962
F33(615)-69-C-1115	ENGINEERING DATA ON NEW AND EMERGING STRUCTURAL MATERIALS	AFML-TR-70-252	AD 720 278
F61052-68-C-0031	IMPROVED PRODUCTION METHOD FOR THIN-WALLED TITANIUM TUBING	AFML-TR-69-310	AD 871 197
F04701-70-C-0059	A REVIEW OF Ti-6Al-6V-2Sn FATIGUE BEHAVIOR	AFML-TR-70-275	AD 710 635
AF33(615)-2499	MANUFACTURING METHODS FOR FORM ROLLING COMPLEX SHAPES OF HIGH STRENGTH TITANIUM ALLOYS	AFML-TR-69-220	AD 861 078
AF33(615)-2742	MANUFACTURING PROCEDURES FOR A NEW HIGH STRENGTH BETA TITANIUM ALLOY HAVING SUPERIOR FORMABILITY	AFML-TR-69-171	AD 857 670
STEEL			
AF33(600)-36713	DEVELOPMENT OF IMPROVED METHODS, PROCESSES, AND TECHNIQUES FOR PRODUCING STEEL EXTRUSIONS	ML-TDR-64-231	AD 608 891
AF33(615)-3159	PRODUCTION PROCESSES FOR EXTRUDING, DRAWING, AND HEAT TREATING THIN STEEL TEE SECTIONS	AFML-TR-68-293	AD 841 689

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
STEEL (continued)			
AF33(657)-9140	FINAL REPORT ON IMPROVED PRODUCTION OF POWDER METALLURGY ITEMS	AFML-TR-65-103	AD 464 368
SUPERALLOYS			
AF33(615)-67-C-1160	PROCESSING TECHNIQUES FOR THE EXTRUSION OF SUPERALLOY POWDERS	AFML-TR-68-321	AD 845 185
AF33(615)-3545	FORM ROLLING CLOSE TOLERANCE SHAPES OF SUPERALLOYS	AFML-TR-69-186	AD 860 456
AF33(657)-9140	FINAL REPORT ON IMPROVED PRODUCTION OF POWDER METALLURGY ITEMS	AFML-TR-65-103	AD 464 368
AF33(615)-2873	MANUFACTURING TECHNIQUES FOR THE EXTRUSION OF SUPERALLOY STRUCTURAL SHAPES	AFML-TR-68-325	AD 846 391
F33(615)-67-C-1341	A MANUFACTURING PROCESS FOR SMALL DIAMETER BAR AND EXTRUDED SHAPES OF TD NICKEL-CHROMIUM	AFML-TR-68-117	AD 834 318
AF33(615)-2872	DEVELOPMENT OF A TUBING AND BAR PROCESS FOR A DISPERSION-STRENGTHENED Ni-Cr-ThO(sub 2) ALLOY	AFML-TR-67-364	AD 824 166
REFRACTORY METAL			
AF33(657)-9140	FINAL REPORT ON IMPROVED PRODUCTION OF POWDER MTTALLURGY ITEMS	AFML-TR-65-103	AD 464 368
AF33(600)-40700	FINAL REPORT ON COLUMBIUM AND COLUMBIUM ALLOY EXTRUSION PROGRAM	AFML-TR-63-637 Volume II	AD 414 462
AF33(615)-2097	SMALL DIAMETER, THIN-WALLED COLUMBIUM TUBING PROGRAM	AFML-TR-66-306	AD 801 698
AF33(657)-11293	FINAL REPORT ON COLUMBIUM H-SECTION EXTRUSION AND DRAWING PROGRAM	AFML-TR-65-32	AD 459 379
AF33(615)-1397	FINAL REPORT ON DEVELOPMENT OF ADVANCED TECHNIQUES FOR THE FABRICATION OF REFRACTORY METAL TUBING	AFML-TR-65-341	AD 474 068

COMPETITIVE PROCESSES

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
AF33(616)-6951	THEORETICAL FORMABILITY	ASD-TR-61-191 Volume I-II	
DA-01-021-AMC11651	DEFORMATION PROCESSING OF TITANIUM AND ITS ALLOYS	NASA-TM-X-54438	
F33(615)-67-C-1164	DEVELOPMENT OF HIGH-TEMPERATURE CONTINUOUS ROLLING PROCESS FOR FORMING MINIMUM-RADII TITANIUM SECTIONS	AFML-TR-69-154	AD 856 359
NOw64-0180-C	PRESSURE TECHNOLOGY CORPORATION OF AMERICAN PROGRESS REPORT, I		
	DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS, VOLUME I	AFML-TR-67-327	AD 856 359
	PROTOTYPE PRODUCTION PROCESS FOR FABRICATION OF WIRE AND TUBING BY HYDROSTATIC EXTRUSION DRAWING	AFML-TR-70-82	AD 870 000
	DESIGN OF A PRODUCTION HYDROSTATIC EXTRUSION PRESS	AFML-TR-68-52	AD 855 302
DAA-H03-69-C-0472	A MANUFACTURING METHOD AND TECHNOLOGY STUDY COVERING FABRICATION OF SMALL-DIAMETER MISSILE MOTOR CASES		
N00419-70-C-0284	EVALUATION OF THE TOOLING DESIGN FOR THE PRODUCTION OF ASROC MOTOR CASE BY HYDROSTATIC EXTRUSION		
DAAG39-71-C-0078	HYDROSTATIC EXTRUSION OF ALUMINUM WAVEGUIDES		
DAAF07-72-C-0360	PRODUCTION OF 60MM MORTAR TUBES BY HYDROSTATIC EXTRUSION		
	HIGH-FREQUENCY RESISTANCE WELDING OF TITANIUM T-SHAPES	AFML-TR-68-382	AD 848 895
F33(615)-69-C-1877	PRELIMINARY INFORMATION, NORTH AMERICAN ROCKWELL CORPORATION		
N0019-69-C-0288	APPLICATION OF THE HEATED ROLL CONCEPT TO HOT ROLLING OF METALS		
F33(615)-72-C-1217	PRELIMINARY INFORMATION FROM SOLAR DIVISION OF INTERNATIONAL HARVESTER COMPANY		
F33(615)-71-C-1672	HYDROSTATIC EXTRUSION OF TITANIUM-ALLOY HYDRAULIC TUBING	IR-243-1(I)	AD 888 063L
AF33(615)-67-C-1160	DEVELOPMENT OF PROCESSING TECHNIQUES FOR THE EXTRUSION OF METAL POWDERS	IR-9-193(I)	AD 805 735
F33(615)-68-C-1268	A "FILLED BILLET" EXTRUSION PROCESS FOR PRODUCTION OF TAPERED TITANIUM STRUCTURAL MEMBERS	AFML-TR-69-177	
F33(615)-67-C-1434	DESIGN OF A PRODUCTION HYDROSTATIC EXTRUSION PRESS	AFML-TR-68-94	AD 855 308
F33(615)-68-C-1197	PROTOTYPE PRODUCTION PROCESS FOR FABRICATION OF WIRE AND TUBING BY HYDROSTATIC EXTRUSION-DRAWING	AFML-TR-70-82	

DRAWING

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
AF33(615)-1674	PRODUCTION TECHNIQUES FOR EXTRUDING, DRAWING, AND HEAT TREATMENT OF TITANIUM ALLOYS	AFML-TR-68-349	AD 848 962
AF33(615)-3159	PRODUCTION PROCESSES FOR EXTRUDING, DRAWING, AND HEAT TREATING THIN STEEL TEE SECTIONS	AFML-TR-68-293	AD 841 689
AF33(615)-67-C-1630	BACK TENSION DRAWING PROCESSES	AFML-TR-69-253	AD 861 485
AF33(615)-67-C-1611	DEVELOPMENT OF CONVEX FACE DRAWN DIE	AFML-TR-69-240	AD 860 711
F33(615)-70-C-1139	ADOPTION OF THE CONVEX DRAW DIE TO THE PRODUCTION OF AIRCRAFT ENGINE RINGS	AFML-TR-72-156	AD 904 032
AF33(615)-70-C-1104	PRODUCTION OF SHAPED SECTIONS WITH CONVEX DRAW DIES	AFML-TR-71-215	AD 890 628L
AF33(615)-71-C-1037	PRODUCTION TECHNIQUES FOR EXTRUDING AND DRAWING BETA III TITANIUM ALLOY SHAPES	NM 6100.20	AD 888 244
AF33(615)-3089	DETERMINATION OF PROCESSING REQUIREMENTS FOR HIGH-STRENGTH TITANIUM ALLOY TUBING MANUFACTURE	AFML-TR-68-263	AD 846 591
AF33(615)-70-C-1680	THE MANUFACTURE OF AIRCRAFT QUALITY TUBING	AFML-TR-71-111	AD 727 779
NAS 3-10602	DEVELOPMENT OF LARGE DIAMETER T-111 (Ta-8W-2Hf) TUBING	NASA-CR-72869	
AF33(615)-2097	SMALL DIAMETER, THIN WALL COLUMBIUM ALLOY TUBING PROGRAM	AFML-TR-66-306	AD 801 698
F33(615)-69-C-1870	MANUFACTURE OF HIGH-STRENGTH RD NICKEL-CHROMIUM TUBING	IR-250-9 (VI)	AD 885 582
AF33(657)-11261	TANTALUM ALLOY TUBING DEVELOPMENT PROGRAM	AFML-TR-67-191	AD 819 050
F33(615)-70-C-1247	ESTABLISHMENT OF MANUFACTURING TECHNIQUES FOR BACK-TENSION DRAWING OF TITANIUM	AFML-TR-73-24	AD 909 268L
AF33(615)-2029	REDRAW TECHNIQUES FOR PRODUCTION OF THIN-WALLED COLUMBIUM ALLOY TUBING	AFML-TR-68-58	AD 831 109
AF33(615)-2872	DEVELOPMENT OF A TUBING AND BAR PROCESS FOR A DISPERSION STRENGTHENED Ni-Cr-ThO(sub 2) ALLOY	AFML-TR-67-364	AD 824 166
AF33(615)-5083	OPTIMUM FORMING PROCESSES AND EQUIPMENT NECESSARY TO PRODUCE HIGH QUALITY, CLOSE TOLERANCE TITANIUM ALLOY PARTS	IR-]009-II	AD 808 877
AF33(657)-11203	EXTRUDING AND DRAWING MOLYBDENUM TO COMPLEX THIN H-SECTIONS	AFML-TR-67-237	AD 822 099

EXTRUSION

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
F33(615)-70-C-1545	MANUFACTURING METHODS OF AN ISOTHERMAL EXTRUSION PROCESS TO PRODUCE 20-FOOT COMPLEX SECTIONS		
F33(615)-70-C-1037	PRODUCTION TECHNIQUES FOR EXTRUDING AND DRAWING BETA III TITANIUM ALLOY SHAPES	AFML-TR-72-97	AD 907 022L
AF33(615)-1390	DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS	AFML-TR-67-327 Volume I	AD 824 227
AF33(038)-23981	STEEL EXTRUSION EXPERIMENTS ON AIRFRAME COMPONENTS	LR-9470	
AF33(615)-3839	TITANIUM PANEL EXTRUSION PRODUCTION PROGRAM	AFML-TR-69-74	AD 853 179
F33(615)-69-C-1892	GLASS BATH HEATING OF FORGING STOCK	AFML-TR-71-15	AD 882 556
AF33(600)-36713	THE DEVELOPMENT OF IMPROVED METHODS, PROCESSES, AND TECHNIQUES FOR PRODUCING STEEL EXTRUSIONS	ML-TDR-64-231	AD 608 891
AF33(657)-11203	EXTRUDING AND DRAWING MOLYBDENUM TO COMPLEX THIN H-SECTION	AFML-TR-67-237	AD 822 099
AF33(600)-36931	PROGRAM FOR THE DEVELOPMENT OF EXTRUDED BERYLLIUM SHAPES		
AF33(657)-9141	FINAL REPORT ON HIGH-TEMPERATURE EXTRUSION LUBRICANTS		
AF33(615)-5247	HIGH PRESSURE EXTRUDING	AFML-TR-69-216	AD 862 626
AF33(615)-1674	PRODUCTION TECHNIQUES FOR EXTRUDING, DRAWING, AND HEAT TREATMENT OF TITANIUM ALLOYS	AFML-TR-68-349	AD 848 962
AF33(615)-3089	DETERMINATION OF PROCESSING REQUIREMENTS FOR HIGH STRENGTH TITANIUM ALLOY TUBING MANUFACTURE	AFML-TR-68-263	AD 846 591
F33(615)-70-C-1680	THE MANUFACTURING OF AIRCRAFT-QUALITY HYDRAULIC TUBING WITH THE Ti-3Al-8V-6Cr-4Mo-4Zr ALLOY	AFML-TR-71-111	AD 727 779
AF33(615)-3159	PRODUCTION PROCESSES FOR EXTRUDING, DRAWING, AND HEAT TREATING THIN STEEL TEE SECTIONS	AFML-TR-68-293	AD 841 689
NAS-8-11448	EVALUATION OF Be-38 PERCENT Al ALLOY		
F33(615)-67-C-1246	PRODUCTION TECHNIQUES FOR THE EXTRUSION OF THIN LOCKALLOY SHAPES	AFML-TR-68-239	AD 841 352
AF33(600)-40700	FINAL REPORT ON COLUMBIUM ALLOY EXTRUSION PROGRAM	ASD-TDR-63-637 Volume I Volume II	AD 413 926 AD 414 462
AF33(657)-11269	EXTRUDING AND DRAWING TANTALUM ALLOYS TO COMPLEX THIN H-SECTION	AFML-TR-66-119	AD 483 623

CONTRACT NUMBER	TITLE	REPORT NUMBER	AVAILABILITY (DDC)
AF33(600)-42395	TUNGSTEN EXTRUSION DEVELOPMENT PROGRAM	ML-TDR-64-217	
AF33(615)-2873	MANUFACTURING TECHNOLOGY FOR THE EXTRUSION OF SUPERALLOY STRUCTURAL SHAPES	AFML-TR-68-325	AD 846 391
F33(615)-71-C-1672	HYDROSTATIC EXTRUSION OF TITANIUM-ALLOY HYDRAULIC TUBING	IR-243-1(I)	AD 888 063L
NObs-94535	PROPERTIES OF BARS, TUBES, AND EXTRUDED SHAPES PRODUCED FROM 10Ni-Cr-Mo-Co STEEL	ARL-B-63101	AD 886 967L
F33(615)-70-C-1375	MANUFACTURING TECHNOLOGY FOR MATERIALS, DESIGNS, AND FABRICATION OF EXTRUSION DIES FOR HOT EXTRUDING OF STEEL AND TITANIUM STRUCTURAL SECTIONS	AFML-TR-73-61	
F33(615)-68-C-1268	A "FILLED BILLET" EXTRUSION PROCESS FOR PRODUCTION OF TAPERED TITANIUM STRUCTURAL MEMBERS	AFML-TR-69-177	AD 858 462
F33(615)-67-C-1434	DESIGN OF A PRODUCTION HYDROSTATIC EXTRUSION PRESS	AFML-TR-68-94	AD 855 308
F33(615)-68-C-1197	PROTOTYPE PRODUCTION PROCESS FOR FABRICATION OF WIRE AND TUBING BY HYDROSTATIC EXTRUSION-DRAWING	AFML-TR-70-82	AD 870 000
F33(615)-67-C-1341	A MANUFACTURING PROCESS FOR SMALL DIAMETER BAR AND EXTRUDED SHAPES OF TD NICKEL-CHROMIUM	AFML-TR-68-117	AD 834 318
AF33(615)-2872	DEVELOPMENT OF A TUBING AND BAR PROCESS FOR A DISPERSION STRENGTHENED Ni-Cr-ThO(sub 2) ALLOY	AFML-TR-67-364	AD 824 166
AF33(615)-2796	DESIGN OF LINERS FOR EXTRUSION OF REFRACTORY METALS	AFML-TR-68-59	AD 832 433
AF33(615)-5080	DEVELOPMENT OF ENGINEERING DATA ON TITANIUM EXTRUSION FOR USE IN AEROSPACE DESIGN	AFML-TR-67-189	AD 818 780
AF33(615)-67-C-1160	DEVELOPMENT OF PROCESSING TECHNIQUES FOR THE EXTRUSION OF METAL POWDERS	IR-9-193(I)	AD 805 735
AF33(615)3048	A PRODUCTION PROCESS FOR LARGE SOLID MOTOR CASES, INTERNAL ROLL-EXTRUDED	AFML-TR-68-116	AD 835 224
AF33(615)-2370	DEVELOPMENT OF AN IMPROVED MANUFACTURING PROCESS FOR THE HOT EXTRUSION OF ALLOY STEEL STRUCTURAL SHAPES	AFML-TR-67-79	AD 813 001
AF33(615)-5317	PROCESS VARIABLES IN METAL EXTRUSION-	AFML-TR-67-242	
	LINER FRICTION DURING EXTRUSION	Part I	AD 827 977
	EXTRUSION DIE FORCES	Part II	AD 841 836
	SUMMARY	Part IV	AD 850 242
DA-19-066-AMC-307(X)	DEVELOPMENT OF A PROCESS FOR PNEUMATIC EXTRUSION OF METALS	AMRA CR 66-04/2	AD 646 993

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10. AVAILABILITY/LIMITATION NOTICES

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	**12. SPONSORING MILITARY ACTIVITY** Manufacturing Technology Division Air Force Materials Laboratories Wright-Patterson Air Force Base, Ohio 45433

13. ABSTRACT

A two-part Design Guide has been compiled to provide technical information and data in the production of structural shapes and tubing for aircraft and aerospace requirements. Part I provides selection criteria for shapes and tubing based on availabilities, design tolerances, and mechanical and physical properties. Part II discusses manufacturing methods for fabricating structural shapes and tubing, namely, extrusion, drawing, and form rolling. Also Part II reviews competitive processes for manufacturing structural type components. This Design Guide is intended to assist design engineers in assessing the availability and properties of materials being considered in new or modified aircraft and aerospace systems, and to assist potential manufacturers and suppliers in assessing equipment, tooling, and processing requirements for fabricating structural shapes and tubing. Materials for aerospace requirements covered in this document include high-strength aluminum alloys, titanium alloys, steels, superalloys, refractory metals, and beryllium.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Selection Criteria						
Design Tolerance						
Structural Shapes						
Tubing						
Aircraft						
Aerospace						
Manufacturing Methods						
Extrusion						
Drawing						
Form Rolling						
High-Strength Aluminum Alloys						
Titanium Alloys						
Steels						
Superalloys						
Refractory Metals						
Beryllium						
Mechanical Properties						
Aircraft Design						